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CURRENT UNDERSTANDING OF CRITICAL GAME SCENARIOS IN TEAM SPORTS: SYSTEMATIC REVIEW

review paper
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ABSTRACT
In sports, game scenarios can be critical or non-critical, potentially presenting very distinct implications for the game flow. However, defining a critical scenario is not an easy task. Although there is some research on game scenarios, game situations, game moments, and critical moments, through this systematic review we intend to fill a gap in the knowledge of critical scenarios in order to structure the existing knowledge and pinpoint current limitations. The search was conducted in July of 2020 in Web of Science, Scopus, PubMed, SciELO, and, through a manual search, in Google Scholar. The eligibility criteria included original research with quantitative and/or qualitative analysis of critical game scenarios or game moments. The participants were humans of any gender, age group, health status, competitive level, or expertise. Risk of bias assessment involved 14 criteria in the evaluation of the studies. The study synthesis methods followed a qualitative synthesis of the main results of each study in the final sample. Of the 279 researched articles, only 4 met the inclusion criteria, i.e. only 4 provided data concerning critical game scenarios. Their contributions are discussed in detail, as is the open research windows for the future. Overall, there is clearly a need for more research specifically addressing this topic, with a huge gap between theoretical relevance and actual investigation.
Key words: performance analysis, match analysis, game moments, critical moments

Introduction

In team sports, a scenario can be defined as a typology of play/game flow that has specific features and implications [1, 2]. Game scenarios contain a set of variables and conditions that are functionally linked and represent a functional whole [3]. Consequently, it is important to categorize the distinct game scenarios as typical of each sport, since this will result in more refined information for structuring the training sessions and constitute an effective tool for performance analysis, allowing coaches to vary the focus of training and improve specific actions in a context close to the real one [4].

In systems analysis, criticality is important in investigating stress and task performance [5], being used to identify important situations and high pressure presence, mainly influenced by the temporal phase and differential score [6, 7]. Game period and score evolution is the situational link of reference to which the subject and the task are inevitably linked [8]. In this context, different game scenarios may have distinct implications and, consequently, some scenarios may have a superior criticality relative to others. Unfortunately, there seems to be no widely accepted term for referring to critical game scenarios. For the most part, expressions such as game moments, critical moments, game scenarios, and others have not been properly defined in the sports sciences literature. Defining critical game scenarios can be quite subjective and influenced by many variables. Therefore, this theme may have a profound relevance in sports, providing a key tool for coaches to manipulate training sessions, e.g. to use high-pressure exercises that are representative of critical game scenarios [9].

In this vein, understanding critical game scenarios contributes to a better comprehension of the performance, as well as better preparation for exhibiting

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well-adjusted dynamic and self-organizational behaviours [10, 11]. However, research seems to be focused on the analysis of concepts such game scenarios in critical and non-critical game moments [12–14]. In fact, critical moments vary depending on their intentionality, which involves the individual's experience combined with time and emotional response [14]. Conversely, a non-critical moment is understood as a response to a performance without contextual pressure [15].

While the study of critical moments is a highly relevant approach, we believe it to be a small part of the broader concept of critical game scenarios [16]. Since critical scenarios portray game-specific situations, they trigger activity in a coherent structure [17], limiting and organizing what the situation means for the subject and for the actions to be successfully carried out of the task, in this case through critical game scenarios, considered one of the performance indicators [18, 19]. Thus, critical scenarios can include: (i) critical moments (time when changes in game state or an unbalanced score occurs depending on time intervals, where these differences have a greater impact on the final outcome of the match [6]); (ii) critical situations (situations where the team is under difficult conditions) [20]) during critical or non-critical moments; and (iii) match status (e.g., winning or losing final score in matches with a small or large difference in goals scored [21]). These should be considered as they have an influence on the performance of the playing patterns of players and teams.

As a consequence of the studies developed on critical scenarios, in our opinion, there seems to be a need to hierarchize and categorize the concepts of critical scenarios and critical moments, so critical scenarios should first emerge because they can occur at a critical or non-critical time.

Studies such as those by Récopé et al. [22] and Sánchez-Moreno et al. [23] have focused on critical scenarios referring to the behaviour of teams in critical or non-critical moments. In order to analyse representations of game actions, as critical game scenarios, the model of Newell's constraints [24] is fundamental to analyse and adapt motor skills because the 3 vectors (task, environment, and individual) are among the ways to classify critical game scenarios. Thus, there is a 2-way interconnection between the model and the critical scenario, as it allows to guide decisions on the provision of appropriate instructions for development. Still, Araújo et al. [25] argued that functional patterns of coordinated behaviour emerged through performers' inter-actions with each other under specific task constraints of a competitive environment. Therefore, critical and non-critical scenarios are relevant in the process of evolution of teams, allowing to simulate them in training and influence the competitive process [26].

The aim of this study was to identify the extent of studies on critical game scenarios and investigate their influence on individual and collective performance, associated with game patterns or game actions. The novelty of this systematic review can be divided into 2 aspects [22, 23]: (a) understanding the theme of critical game scenarios (what they represent and to how teams both influence and are influenced by those critical scenarios); (b) assessing how critical game scenarios are being investigated through the lenses of performance analysis. As previously established, critical scenarios include but are not limited to critical moments [6, 16, 20].

Material and methods

Eligibility criteria

Articles were eligible if they were published or accepted, with full text in English. No limitations were imposed on the date of publication. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were adopted. The PICOS process was established as follows: (i) the participants had to be human, regardless of sex/gender, age group, health status, competitive level, or level of expertise; (ii) all interventions using match analysis were considered critical game scenarios or game moments, with no limitations with regard to the sport; (iii) comparators were non-critical scenarios; (iv) outcomes were any effects on performance; (v) the study design was limited to original research with any type of quantitative and/or qualitative game analysis. This study was approved by the Ethics Committee at the Centre of Research, Education, Innovation and Intervention in Sport of the University of Porto (09 2020 CEFADE).

Information sources and search

Databases used for this research were: Web of Science, Scopus, PubMed, and SciELO. The search was conducted in July of 2020. The search protocol used Boolean operators and the title or abstract or keywords (in Web of Science, this combination is termed 'Topic' and also includes keywords; Scopus also includes keywords) had to contain: (i) "match scenarios" OR "game scenarios" OR "game situations" OR "game moments" OR "critical moments" OR "critical scenarios"; (ii) AND differences OR variation OR variations OR distinct OR variability; (iii) AND sport OR sports OR games. No limitations were imposed on the date of publication. In Scopus, the document type filtering was limited to article. In SciELO, 2 separate searches had to be conducted: one for title and another one for abstract. Also, a manual search was performed in Google Scholar.

Study selection

The initial screening provided 277 results (91 in Web of Science, 167 in Scopus, 19 in PubMed, and 0 in SciELO). After this electronic search, we performed a manual search in Google Scholar to ensure greater robustness in the study, and 2 more studies were included (n = 279) The identified articles were then exported to Mendeley reference manager software (Freemium, version 1803, Elsevier, Amsterdam). After the removal of duplicates, 195 records remained that were considered eligible for further scrutiny. After the initial screening of the title and abstract, 160 articles were excluded for being outside the scope and the remaining 35 went for full-text analysis.

At this stage, 31 articles were excluded. The following were excluded because they were unrelated to the theme of this review, despite having promising titles and abstracts: Andrienko et al. [27], Bartlett et al. [28], Blomqvist et al. [29], Evans et al. [30], Rojas Ferrer et al. [31], Filipcic et al. [32], French et al. [33], González-Víllora et al. [34], Klostermann et al. [35], Kokoulina et al. [36], Koo et al. [37], Lupo et al. [38], McPherson [39], Praça et al. [40], Schläppi-Lienhard and Hossner [41], Sevil Serrano et al. [42], Uljevic et al. [43], and Zubillaga et al. [44]. The following articles were eliminated because they did not present relevant data on the theme of this research: Batista et al. [13], Cañadas et al. [45], Connor et al. [46], Ferraz et al. [47], Gomez et al. [48], Gonçalves et al. [49], Lupo et al. [50], Millslagle [51], and Ramos et al. [52]. An article by Ferreira et al. [53] was eliminated because it dealt with coaches and non-athletes. Likewise, articles by Medina et al. [54], Reina et al. [55], and Pombo et al. [56] were excluded because the body of the paper was written in Portuguese or Spanish.

Thus, the final sample consisted of 4 original research papers [22, 23, 57, 58]. The data for the 4 articles are detailed in Table 1.

Data collection process

The main author conducted the initial search. One week after the initial search, 2 co-authors repeated the search to ensure the quality of this first step. All the authors reviewed the entirety of the retrieved papers to decide which ones to include and which to exclude. In cases of disagreement, the authors discussed the article in detail and re-analysed it to ensure the quality of this step.

Data items

For the papers included in the analysis, the following data items were considered: sample (e.g., athletes, sex/gender, age group in game analysis context, level of game, and experience), main methodological procedures (details of the protocols and tests), variables analysed, and main evidence.

Risk of bias in individual studies
and across studies

The tool used in this investigation was the same as Clemente et al. [59] applied in their study, being an adapted version of the tool utilized by Sarmento et al. [60]. It served to evaluate the studies (with the answers of yes, no, or not applicable) with the consideration of 14 criteria: the purpose of the study (item 1), the presence of the most relevant literature (item 2), the appropriate design for the investigation (item 3), the description of the sample (item 4), the justification of the sample size (item 5), the indication of the use of informed consent (item 6), the correctness of the measures of the results (item 7), the validation of the results (item 8), the detailed description of the methods (item 9), the reporting of the results in terms of statistical importance (item 10), the adequacy of the methods of analysis (item 11), the adequacy of conclusions based on the methods (item 12), the existence of practical implications (item 13), and recognition and description of the limitations of the study (item 14). The 14 quality criteria were marked by using a binary scale (i.e. 0 or 1). However, item 6 also had an option of 'If not applicable, assume NA'. Two of the authors classified the complete articles included in the sample. The agreement consisted in the agreement of both, and the answers of each tested through the kappa coefficient (κ) were used to measure the reliability rate between the reviewers.

Ethical approval

The conducted research is not related to either human or animal use.

Results

Study selection

The original search in the databases returned 279 articles. After 84 duplicated articles were excluded, 195 papers were screened for relevance on the basis of their title and abstract; 160 studies were excluded. Therefore, 35 articles were analysed in detail. Out of these, 31 were rejected because they did not meet the inclusion criteria. At the end of the screening procedure, only 4 articles were included for in-depth and full reading and analysis (Figure 1).

Characteristics and results of individual studies

The complete data items for individual studies can be found in Table 1.

Récopé et al. [22] studied intra-team differences in defence-related game scenarios. They conducted 2 case studies. In the first one, the sample comprised 31 professional male volleyball players from 2 national teams, who were observed during 3 games in the World League. In the second case, the sample included 12 players (6 representatives of population A and B each, composed of a selection of 3 members of each national team). These case studies developed a systematic observation of the behaviour of players in specific defensive situations. The main evidence was: (1) the existence of differences between groups of high-level volleyball players in the defensive context; (2) the identification of a specific overall coherence that guides and organizes a defensive activity. We highlight that in this study, the time pressure, the evaluation of the situation, and the way of performing the actions are highly connected, but also organized and guided by the subconscious sense of the athlete.

Sánchez-Moreno et al. [23] analysed how the length of the rally affected the performance in accordance with the final action of the rally and the level of play, as well as identified potential critical rallies associated with the length of the rally in men's volleyball. In

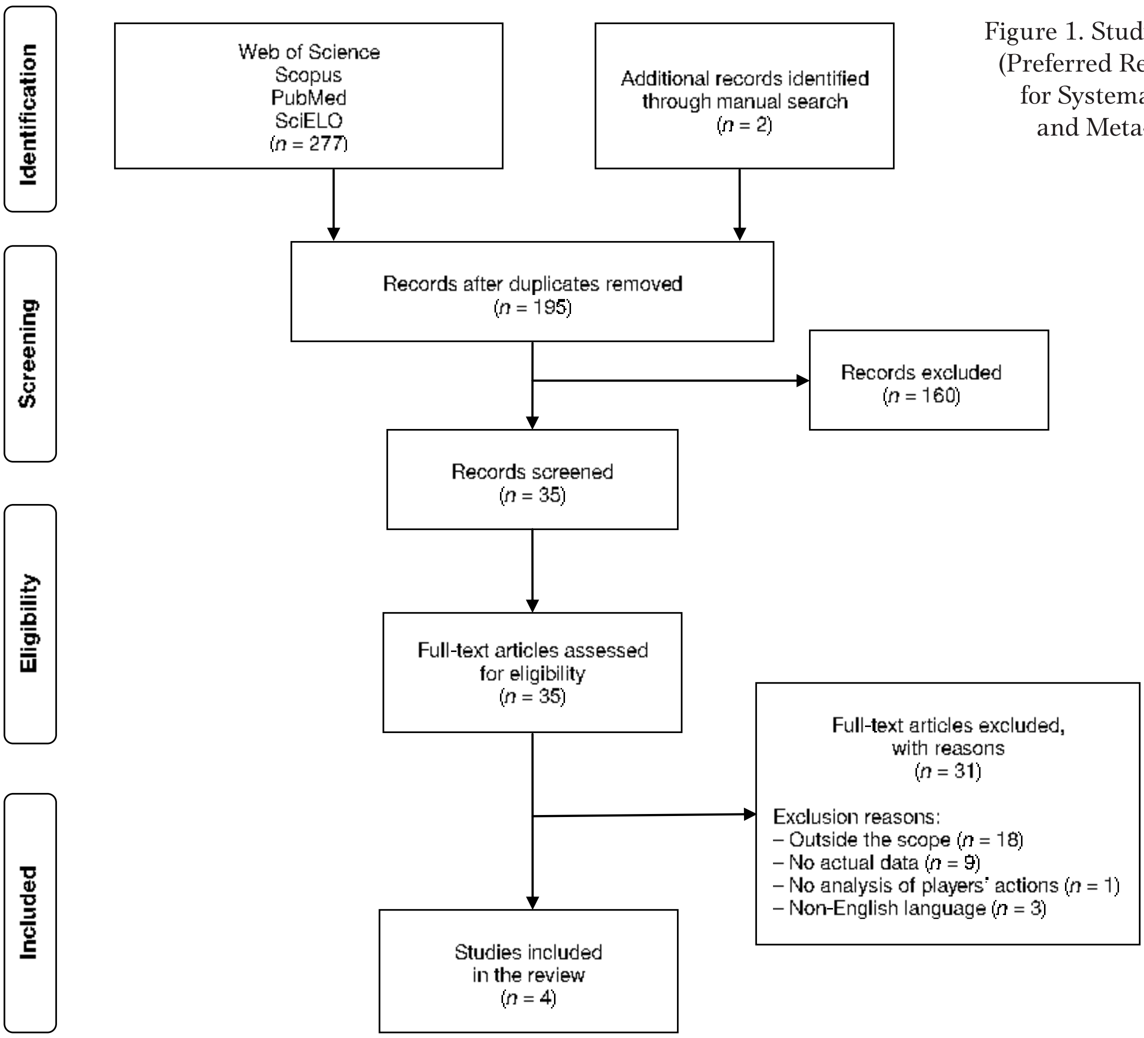

Figure 1. Study flow diagram (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

Table 1. Data items for the individual studies

Authors	Sample	Methodological procedures	Variables analysed	Main evidence
Récopé et al. [22]	Two cases studies: Case 1: 31 professional male volleyball players from national teams were observed during 3 matches in the World League Case 2: 12 players (6 from population A, comprising 3 members of each national team, and 6 of population B, comprising 3 members of each national team)	Case 1: Systematic observation of the players' behaviour in specific defensive scenarios Case 2: Two types of qualitative data were collected through the results of case 1. Performed audio-visual recordings of the 12 players' activity with focus on relevant extracts of film concerning their actions during the selected defensive situations identified from case 1	Case 1: Behaviour and set of game situations: (1) characteristics of body posture; (2) characteristics of the player's intervention; (3) result-based dissatisfaction reactions after losing a rally in defensive action Case 2: (1) relevant cues; (2) expectancies; (3) plausible goal; (4) typical action	Cases 1 and 2: The various components of activity are the contextual actualization, at various scenarios and in accordance with the current circumstances. The high time pressure, situation assessment, and course of action seem highly coupled, but also organized and normed by this subconscious sense. If a subject has not enough time to consider several options before implementing one of them, the results lead to consider that this subconscious sense orients and organizes the individual activity (the situation assessment and the current action). Results lead to (1) an objectification and characterization of differences between 2 populations of elite volleyball players in a defensive context; (2) the identification, for each population, of a specific overall coherence that orients and organizes the defensive activity of its members
Sánchez-Moreno et al. [23]	5438 rallies retrieved from 31 matches of volleyball (121 sets) were sampled from 2010 Men's World Championship and Men's World League	An exhaustive Chi-square Automatic Interaction Detector growing method was applied as a visual and analytical multivariate decision support tool where the expected values of competing alternatives were calculated	Rally length, success of the team in the side-out phase, teams' ranking, and final action of the rally	Rallies between 8 and 10 seconds emerged as potential critical incidents of the game. These rallies seem to change the general trend in performance in accordance with the final action that finishes the rally. When the rally does not end with the first attack, the team in the serve phase can attack and has a greater chance to score. More than 10-second rallies seem to balance success between teams
Sarajärvi et al. [57]	920 headers performed in 9 English Premier League of football games from the season of 2017–2018	Nine match weeks were randomly selected. In each match week, one game was randomly selected. No team was included twice in the sample. Only the actions where a player intentionally contacted the ball were considered. Accidental touches were not coded	Game state, space of occupation, header location, set play type, number of opponent players, and the position of the player executing a header	Headers are game scenarios that have different moments and executions. A high occurrence of this scenario was used in long balls or even through crosses or throws, in order to avoid spatial progression of the attacking team. Almost half of the headers were executed during the set plays, especially on-goal kicks and throws. A considerable number of headers were executed in the centre of the penalty. Central defenders executed many interceptions and clearances of crosses, while forwards often used their heads to pass the ball
Villemain and Hauw [58]	11 male goalkeepers from the French national football training centre	2 steps in data collection: (1) identification of typical critical game situations; (2) description of each critical situation through interviews (questioning interview). Questions were formulated by using present tense, brief sentences, and verbs of action	Five categories related to critical scenarios: (1) main topic; (2) actions (means to achieve goal); (3) attention contents (focus on perceptions); (4) background (knowledge mobilizes during the action); (5) inner states	23 critical game situations were ranked into 4 typical critical situations: coming off the line, goal-line clearances, one-on-one, and diving were formulated as recurrent critical game situations for goalkeepers. Coming off the line represented the main critical game situation for all goalkeepers. Goal-line clearance and one-on-one were also mentioned as recurrent critical situations for 5 players. Diving was reported only twice as a critical situation

the 2010 World Championship and men's World League, there were 5438 rallies in 31 games. The support tool used was the Chi-square Automatic Interaction Detector method, which allows a visual and analytical multivariate decision, where the expected values of competing alternatives were calculated. The variables considered in this study were the length of the rally, the success of the team in the side-out, the ranking of the teams, and the final action of the rally.

As main evidence, we highlight the rallies between 8 and 10 seconds that emerged as potential critical incidents of play, and these rallies changed the trend of performance in accordance with the final action of the rally. For example, when a rally does not end in the first side-out attack, it means that the team in possession of the service can attack and increase the chances of scoring. On the other hand, rallies with more than 10 seconds seem to balance the chances of success between both teams.

Sarajärvi et al. [57] studied the headers in high-performance football and characterized how they were executed in different game scenarios. The sample consisted of all headers made in 9 English Premier League, 920 headers of the 2017–2018 season. First, 9 weeks of play were randomly selected, and secondly, from each week of play, a game was selected for the study. Only actions in which a player intentionally contacted the ball were considered. The main evidence was as follows: (1) a high number of headers were executed to prevent the spatial progression of the attacking team, the method most used through long balls; (2) half of the headers were executed during the plays, especially on penalties and throws; (3) a considerable number of headers were executed near the penalty mark; (4) central defenders executed many interceptions of crosses, while forwards used their heads to pass the ball.

Finally, Villemain and Hauw [58] investigated the activity and performance of elite football goalkeepers in critical situations. Eleven male goalkeepers from the training centre of the French Football Federation were considered. Methodologically, they took 2 steps in data collection: the first one associated with the identification of typical game situations and the second one associated with the critical scenario.

Interviews were used to obtain the results, and each critical scenario resulted in an interview. Five categories related to critical scenarios were applied: main topic, actions (means to achieve the goal), attention contents, background, inner states. For each critical game scenario, attention focused on the specific moment defined by the player (start to the end of the action). Twenty three critical situations of the goalkeepers were recurrent, being classified in 4 critical scenarios: coming off the line, goal-line clearances, one-on-one, and diving. Coming off the line represented the main critical game situation for all goalkeepers. The goal-line clearances and the one-on-one were referred to as recurrent critical situations for 5 of the 11 players. Diving was reported only twice as a critical situation.

Risk of bias within and across studies

All studies (Table 2) presented a low risk of bias arising from the randomization process. This agreement consisted in analysing the level of agreement of the answers, by using the kappa coefficient (κ), revealing an agreement of κ = 1.0. The agreement was high in all studies, with no divergence of responses.

Discussion

The analysis of critical game scenarios, in both critical and non-critical game moments, can theoretically provide an innovative perspective on match performance [23], helping to differentiate critical vs. non-critical scenarios and therefore providing more refined information for the coaches to act upon. The goal of this research was to systematically review studies focused on critical game scenarios in team sports and assess their findings. Four relevant databases (PubMed, SciELO, Scopus, and Web of Science) were searched, and an additional manual search was performed. Of the 279 articles identified, only 4 fit the eligibility criteria. Many of the excluded articles were duplicates, and numerous were theoretically driven works, but empirical studies on this topic were scarce.

In the 4 included articles, 4 common features can be highlighted: (i) they all address critical scenarios associated with game situations and the relevance of knowing how to perform under non-ideal game situations; (ii) these critical scenarios are usually, but not always, associated with time pressure and, consequently, game patterns present distinct features under these conditions in comparison with non-critical scenarios; (iii) overall, the literature on the topic and the framework of critical scenarios require further elaboration, systematization, and exploration; (iv) finally, all studies underlined how critical scenarios are crucial to understanding the development of game actions. Hence, a first finding was that research addressing the topic of critical scenarios is severely limited. Because critical scenarios reflect specific game situations and trigger activity in a cohesive structure [17]

Table 2. Risk of bias in individual studies and across studies

Questions	By main author				By 2 co-authors			
	Récopé et al. [22]	Sánchez-Moreno et al. [23]	Sarajärvi et al. [57]	Villemain and Hauw [58]	Récopé et al. [22]	Sánchez-Moreno et al. [23]	Sarajärvi et al. [57]	Villemain and Hauw [58]
Was the study purpose stated clearly?	1	1	1	1	1	1	1	1
Was relevant background literature reviewed?	1	1	1	1	1	1	1	1
Was the design appropriate for the research question?	1	1	1	1	1	1	1	1
Was the sample described in detail?	1	1	1	1	1	1	1	1
Was the sample size justified?	1	1	1	1	1	1	1	1
Was informed consent obtained?	1	NA	NA	1	1	NA	NA	1
Were the outcome measures reliable?	1	1	1	1	1	1	1	1
Were the outcome measures valid?	1	1	1	1	1	1	1	1
Was the method described in detail?	1	1	1	1	1	1	1	1
Were the results reported in terms of statistical significance?	1	1	1	1	1	1	1	1
Where the analysis methods appropriate?	1	1	1	1	1	1	1	1
Were conclusions appropriate given the study methods?	1	1	1	1	1	1	1	1
Are there any implications for practice given the results of the study?	1	1	1	1	1	1	1	1
Were limitations of the study acknowledged and described by the authors?	1	1	1	1	1	1	1	1

1– yes, 0 – no, NA – not applicable

that is likely very distinct from that in more regular, non-critical game scenarios, the observation indicates that this concept is being explored in a limited manner.

The study by Récopé et al. [22] linked game situations in volleyball to critical scenarios of the ball trajectories. From this study, we note that critical scenarios (which are representative of game actions at specific stages with instability in the environment) imposed by the unstable and variable temporal dynamics of the game appear to be important in sports games, including volleyball, where tempo is conditioned externally by regulation (giving greater predictability). As such, critical scenarios can serve as an important resource in training for increasing or decreasing pressure. Because time pressure allows players to deal with the pressures of the team's game system and thus to develop quick and efficient decision-making [7], it deserves further investigation by research. Moreover, critical scenarios have a time limit and this experience is central to the result of the action as these scenarios are emotionally charged, evolve the player, and allow a performance resulting from the processing of relevant information [61].

The studies by Villemain and Hauw [58] and Sarajärvi et al. [57] investigated actions in football that required high emotional control. The outcomes of these actions can directly dictate the game result. These studies focused on the actions to be performed in each scenario, the attention and experience of the players, and their emotions in critical scenarios [58]; and the state of the game, the location of the header, the number of opponents, and the position of the player at the time of the header [57]. These papers imply that the critical scenarios of the game have a component of great specificity as they help reinforce the importance of concentration and self-confidence, and thus progress the general idea that focus, attention, positioning, and presence are necessary for excellent performance [18].

A further aspect of critical game scenarios is that the regulation of independent structures influences the dynamic functionality of teams [12] to the extent that critical game scenarios can be differentiated on the basis of game style, team characteristics, game stages, and gameplay actions.

In this line, we highlight the clear relationship between critical scenarios, game phases, and gameplay

[62] because these critical scenarios and their moments support research on risk situations (through rally length, team success, team ranking, and final action) aiming to improve adaptation to the various situations that occur in the game [58, 63]. Thus, we note that critical scenarios have a strong positive influence on the evolution of teams and on the design of performance strategies [64]. Contrary to what was advocated in this review – that critical scenarios play a key role in sports games – Villemain and Hauw [58] suggested, after a focus on several critical scenarios, that this is not always the case. While many critical scenarios influence game outcomes, others have little impact. The environment of critical scenarios allows players to use informational restrictions to regulate their actions, on the basis of the team's decision, to influence their opponents behaviour [65]. Therefore, critical scenarios are central to understanding teams' perceptions. It is complex and difficult to define environment and players' perspectives as main actors of the game may provide deeper information for their study, with players describing their experience and action in each critical scenario in the header and loss of the ball [57, 58]. Thus, research on critical scenarios can be expanded to include other, less-studied issues, such as their association with cognitive flow [66], which allows athletes to think and make decisions based on the variables involved and not just spontaneously.

The studies included in the final sample support the assumption that it is necessary to focus on critical scenarios to help clarify which game situations should and should not be considered as critical. Indeed, the 4 studies included in this systematic review can be considered pioneering research as they represent the only systematic investigations of critical scenarios and provide important research avenues for the future. The main findings support the idea that critical scenarios correspond to the representation of game contexts, at a certain stage of play, occurring in great complexity and with extreme emotional conditions. As such, we highlight the need to specify the definition of critical game scenarios and its associated terminology to avoid incorrect usage of the concept. It is noteworthy that because the number of eligible studies on critical scenarios was small, we subsequently reviewed non-experimental research; however, no more articles were considered.

Conclusions

The results of the systematic review show that critical scenarios have been neglected and largely unexplored in research. Further studies on this topic are necessary because: (a) terminology in the available literature suggests that scenarios have been studied, but research specifically investigating critical scenarios is scarce; (b) a substantial body of work exists that misuses constructs and concepts, often incorrectly defining non-critical situations as being critical; (c) critical scenarios allow a systematic evolution of teams and a better knowledge of the game; (d) teams deal with time pressure and make faster and more efficient decisions; (e) critical scenarios can have 3 features that are essential for better individual and collective performance; (f) critical scenarios can be influenced by independent structures that help team dynamics; and (g) in critical scenarios, there can be variation in the form of critical manifestations that will lead to different measures. The small number of articles shows that although critical scenarios are theoretically relevant, they remain largely uninvestigated, hence highlighting the need for further research. As such, future studies should focus on high-level critical scenarios, use specific game exercises, and, consequently, apply more high-level investigations, as well as adopt a multidimensional perspective through the frequency of scenarios.

Disclosure statement
No author has any financial interest or received any financial benefit from this research.

Conflict of interest
The authors state no conflict of interest.

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PREVALENCE OF CARDIOVASCULAR RISK FACTORS IN ADULTS REGISTERED IN A PRIMARY HEALTH UNIT OF PORTO

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ABSTRACT
Purpose. The study aims to describe the adult's overall cardiovascular disease risk factors prevalence, including arterial stiffness and physical inactivity.
Methods. The cross-sectional study involved 197 adults (males: 42%; mean age: 47 ± 13 years) from a Portuguese health centre. Traditional cardiovascular disease risk factors were measured during clinical assessment. Arterial stiffness was evaluated with carotid-femoral pulse wave velocity (≥ 10 m/s). Physical inactivity (< 30 min/day of moderate to vigorous physical activity) was objectively assessed with accelerometry. The statistical procedures included descriptive analysis (means, medians, and frequencies) and between-gender comparisons (chi-square test and *t*-test) for cardiovascular disease risk factors.
Results. Cardiovascular disease risk factors prevalence was as follows: dyslipidaemia: 71%, physical inactivity: 51%, hypertension: 43%, metabolic syndrome: 36%, arterial stiffness: 31%, smoking: 29%, and obesity: 20%. The prevalence of cardiovascular disease risk factors increases with age and is higher in males than in females. The prevalence of hypertension and metabolic syndrome was higher in participants with a lower educational level. The majority of hypertensive patients were more physically inactive (56.5%) than active (43.5%; $p = 0.044$).
Conclusions. The overall prevalence of cardiovascular disease risk factors was high, with 1/3 having augmented arterial stiffening and half being physically inactive.
Key words: epidemiology, prevalence, cardiovascular risk factors, lifestyle, physical activity

Introduction

Despite the reduced trend observed in the recent decades, coronary artery disease and stroke are still among the major causes of premature death in Portugal and across the European countries [1]. Both conditions contribute to disability and to the mounting costs of healthcare, which could be primarily reduced through early detection and management of their determinants [2].

Cardiovascular diseases (CVD) are strongly related to biological, socio-demographic, and lifestyle risk factors, historically divided into modifiable or non-modifiable ones [1]. The presence of only one risk factor augments the probability of a CVD event, but a grouping of several implies an exponential growth in that probability [3]. Metabolic syndrome (MetS) is a good example of a cluster of risk factors which doubles the probability of cardiovascular events [4].

Apart from the traditional, well-known risk factors, other biological markers have been proposed as independent predictors of cardiovascular events and cardiovascular mortality [5]. However, some of them are not yet included in cardiovascular surveillances and risk stratifications owing to methodological constraints in clinical practice. Arterial stiffness is an adequate example of one biological marker that could help in the early detection of high-risk patients and, consequently, in the early control and management of cardiovascular risk [5, 6]. Arterial stiffness denotes an augmented rigidity of the central large arteries, and is a consequence of intima and media layers structural changes resulting from multiple cellular insults across the lifespan [7]. Previous evidence reports that indi-

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viduals with high compared with those with normal arterial stiffness have a superior cardiovascular event risk (relative risk: 2.26; 95% confidence interval: 1.89–2.70) and cardiovascular mortality (relative risk: 2.02; 95% confidence interval: 1.68–2.42) after adjusting for traditional risk factors [5]. Nevertheless, measuring arterial stiffness as a cardiovascular risk factor in primary care setting is still unusual, and, generally, reports on CVD risk factors do not encompass it.

Regular surveillance and screening for CVD risk factors are relevant in clinical settings because they allow to properly manage each risk factor and thus to diminish the risk of CVD events and mortality. Therefore, the study aims to describe the overall prevalence of CVD risk factors, including arterial stiffness and physical inactivity, in adults registered in a Portuguese primary care centre.

Material and methods

Study design

The study was carried out in a public primary care medical centre (Porto, Portugal). The inclusion criterion was age between 18 and 65 years. Participants with a history of severe hypertension, peripheral arterial disease, arrhythmia, acute coronary syndrome, thyroid disorders, severe renal or pulmonary disorders, infectious or chronic immunological diseases, neurological or orthopaedic deficiencies, known CVD, or cognitive disorders were excluded.

Participants

The patients were recruited from the medical centre archives that involved 8000 citizens. Overall, 4600 individuals were considered candidates following the inclusion criteria, and 1200 were randomly chosen (see Figure 1). They were invited to the study via phone calls. More details can be found elsewhere [8].

Data collection

Data were collected during 2 appointments. In the first appointment, a physician checked eligibility conditions, collected socio-demographic information and habitual medication data. After that, the participants were evaluated for anthropometry and haemodynamics. Finally, each subject received an accelerometer to be worn for the next 7 days. A week later, the patients revisited the health centre in order to return the accelerometers and provide blood samples.

Cardiovascular risk factors

Socio-demographic factors

Age was categorized in decades, and education involved 3 categories based on the number of years schooling (< 6 years, 6–12 years, and > 12 years).

Tobacco consumption

The participants had to indicate whether they smoked or not.

Obesity

Body weight (kg) (Tanita Inner Scan BC-522, Tokyo, Japan) and height (m) (standard wall-mounted stadiometer) were measured with the patients barefoot and wearing light clothing. Body mass index (BMI) was calculated as the ratio of weight (kg) and squared height (m), and classified as underweight (≤ 18.49 kg/m^2), normal weight (18.50–24.99 kg/m^2), overweight (25–29.99 kg/m^2), and obese (≥ 30 kg/m^2).

Blood pressure

Blood pressure was measured (Colin, BP 8800 monitor, Critikon, USA) on the participants' left arm after 20-minute resting, in the supine position. Three measurements were performed spaced 1 minute apart. The average value was used as the final blood pressure. Additional measurements were performed when differences between readings surpassed 5 mm Hg, being the extreme value discarded for the final calculation of blood pressure. Hypertension was defined as stated in the European Society of Cardiology and European Society of Hypertension guidelines (i.e., systolic blood pressure ≥ 140 and/or diastolic blood pressure ≥ 90 mm Hg or presence of antihypertensive medication) [3].

Arterial stiffness

Arterial stiffness was measured with the gold-standard method known as carotid-femoral pulse wave velocity (cfPWV) by using applanation tonometry (SphygmoCor device; AtCor Medical, Australia). The procedures followed the international best practices described elsewhere [6]. Two acceptable attempts of cfPWV were achieved, and the average between them was used for statistical procedures. The cut-off point of cfPWV ≥ 10 m/s was used to establish augmented arterial stiffness [6]. Room temperature was set at ca. 21°C, and the space was both quiet and semi-dark.

Dyslipidaemia

A nurse collected blood samples after 12-hour fasting. An automated clinical chemistry analyser Olympus AU5400 (Beckman-Coulter) was used to measure total cholesterol, triglycerides, high-density lipoprotein cholesterol, and serum glucose. The Friedewald equation was applied to calculate low-density lipoprotein cholesterol concentration. Any lipid impairment in accordance with the international reference values [9] and/or a current prescription of lipid-lowering medication was stated as the presence of dyslipidaemia [3].

Metabolic syndrome

MetS is a condition defined as the simultaneous coexistence of a minimum of 3 metabolic risk factors out of the following: central obesity (male waist circumference ≥ 102 cm, female waist circumference ≥ 88 cm); systolic ≥ 130 mm Hg and/or diastolic ≥ 85 mm Hg blood pressures and/or antihypertensive medication; low levels of high-density lipoprotein cholesterol (males: < 40 mg/dl, females: < 50 mg/dl) or specific lipid treatment; triglycerides ≥ 150 mg/dl and/or specific lipid-lowering treatment; and fasting glucose ≥ 100 mg/dl or medication for elevated glucose level [4].

Physical activity

Physical activity was accurately captured with accelerometry (ActiGraph GT1M, USA). The apparatus was placed on the right hip during waking hours for 7 consecutive days, but removed during water-based activities.

Raw activity (i.e., counts/min) was transformed into daily physical activity (ActiLife 6.9 software, ActiGraph, USA). The accelerometry data were validated when the participants had at least 8 hours of use per day, and 4 days of use. The cut-off point ≥ 2020 counts/min was applied to ascertain moderate to vigorous physical activity [10]. The total time spent above the cut-off point was summed and averaged per day. The risk factor of physical inactivity was set as < 30 min/day in moderate to vigorous physical activity [11].

Statistical analysis

Normality was verified by using the Kolmogorov-Smirnov test. Variables that were not normally distributed (BMI, systolic blood pressure, cfPWV, high-density lipoprotein cholesterol, low-density lipoprotein cholesterol, total cholesterol, triglycerides, and fasting glucose) were transformed into their natural logarithm for analysis and then transformed back to the original scale for the purpose of clarity. These variables are expressed as mean ± standard deviation. Moderate to vigorous physical activity was not normally distributed and normalization was not possible. In this sense, moderate to vigorous physical activity is expressed as median and interquartile range. Between-gender comparisons were performed by using the independent *t*-test and the non-parametric test for 2 independent samples, as appropriate. Categorical variables are expressed as frequencies, and between-group comparisons were performed with the chi-squared test.

The procedures were carried out with the IBM SPSS 20 software (SPSS, Chicago, USA), and the results were considered significant at $p < 0.05$.

Ethical approval

The research related to human use has complied with all the relevant national regulations and institutional policies, has followed the tenets of the Declaration of Helsinki, and has been approved by the Ethics Committee of the Portuguese North Regional Health Authority (I.P. 25/2010).

Informed consent

Informed consent has been obtained from all individuals included in this study.

Results

A total of 318 patients from the sampled 1200 missed the phone call. Additional 244 refused to participate, and 348 met at least one of the exclusion criteria. Overall, 290 scheduled the first appointment, but 33 missed it.

Out of the 257 adults who participated in the study, 197 had simultaneous data for biochemical analyses, physical activity, and arterial stiffness; they comprised the final sample (Figure 1).

Table 1 depicts the sample characteristics. The genders were significantly different for total cholesterol (males: 189.2 ± 37.5 mg/dl, females: 203.1 ± 38.5 mg/dl; $p < 0.05$), diastolic blood pressure (males: 76.5 ± 10.3 mm Hg, females: 73.3 ± 11.0 mm Hg; $p < 0.05$), triglycerides (males: 121.6 ± 63.3 mg/dl, females: 103.8 ± 48.6 mg/dl; $p < 0.05$), and high-density lipoprotein (males: 48.0 ± 10.9 mg/dl, females: 61.7 ± 15.3 mg/dl; $p < 0.001$).

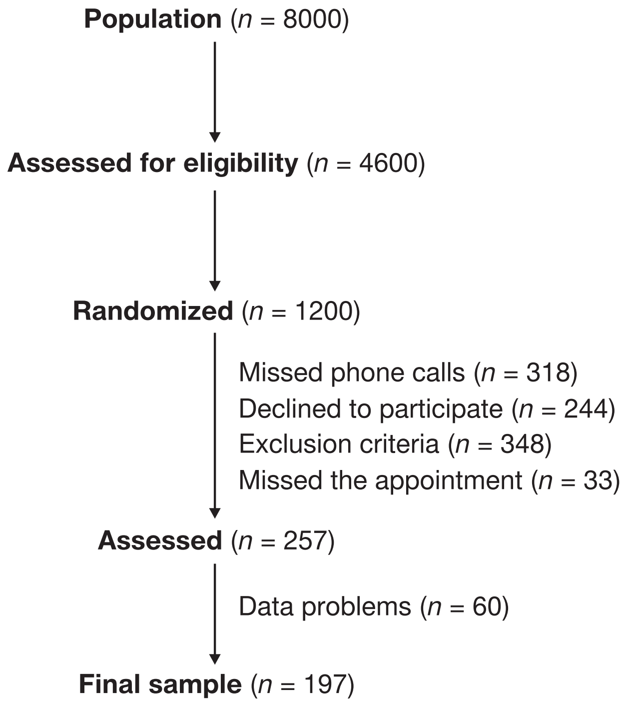

Figure 1. Study flowchart

The prevalence of CVD risk factors is depicted in Table 2. Overall, 71% of the participants had dyslipidaemia. Physical inactivity was the second most prevalent risk factor (overall prevalence: 51%), with females showing a tendency to be more physically inactive compared with males (p = 0.053). The cfPWV value ≥ 10 m/s was the fifth most prevalent risk factor (31%). A significant difference was observed between genders in smoking, with males (40%) having a higher prevalence than females (22%; p < 0.01).

The prevalence of hypertension, dyslipidaemia, and MetS rises with age. These occurred more often in the overweight BMI category and among non-smokers (Table 3). In females, hypertension was significantly more frequent in those physically inactive (67%) than in physically active (33%; p = 0.044).

Regarding arterial stiffness, the prevalence of hypertension, dyslipidaemia, and MetS were higher in the category of cfPWV ≥ 10 m/s compared with the normal, but the differences were not significant (p = 0.568, 0.081, and 0.296, respectively).

Table 1. Sample characteristics with between-gender comparisons

Characteristics	Males (*n* = 83)	Females (*n* = 114)	Overall (*n* = 197)
Socio-demographic			
Age (years)	47.5 ± 13.7	47.3 ± 12.4	47.4 ± 12.9
Educational level (*n* [%])			
< 6 years	25 (30%)	43 (38%)	68 (35%)
6–12 years	21 (26%)	18 (16%)	39 (20%)
> 12 years	36 (44%)	52 (46%)	88 (45%)
Anthropometric			
Height (cm)	170 ± 6.5	157 ± 6.5**	163 ± 9.3
Weight (kg)	78.9 ± 12.0	65.8 ± 12.5**	71.3 ± 13.9
Body mass index (kg/m^2)	27.1 ± 3.9	26.6 ± 4.6	26.8 ± 4.3
Haemodynamic			
Systolic blood pressure (mm Hg)	127.7 ± 14.2	126.1 ± 17.7	126.8 ± 16.3
Diastolic blood pressure (mm Hg)	76.5 ± 10.3	73.3 ± 11.0*	74.7 ± 10.8
Pulse wave velocity (m/s)	9.2 ± 1.8	8.9 ± 2.0	9.1 ± 1.9
Lipid and metabolic profile			
Triglycerides (mg/dl)	121.6 ± 63.3	103.8 ± 48.6*	111.4 ± 55.9
LDL cholesterol (mg/dl)	117.4 ± 35.1	120.0 ± 36.6	118.9 ± 35.8
HDL cholesterol (mg/dl)	48.0 ± 10.9	61.7 ± 15.3**	55.9 ± 15.2
Total cholesterol (mg/dl)	189.2 ± 37.5	203.1 ± 38.5*	197.1 ± 38.6
Fasting glucose (mg/dl)	98.1 ± 18.2	94.7 ± 35.7	96.1 ± 29.5
Physical activity			
MVPA (min/day)	33 (20–54)	26 (16–48)	30 (18–50)

LDL – low-density lipoprotein, HDL – high-density lipoprotein, MVPA – moderate to vigorous physical activity
* p < 0.05, ** p < 0.001

Table 2. Prevalence of risk factors with between-gender comparisons

Risk factors	Overall	Males	Females	Statistical inference
Dyslipidaemia (*n* [%])	140 (71%)	61 (74%)	79 (69%)	χ^2: 0.411 (1); p = 0.316
Physical inactivity (*n* [%])	100 (51%)	36 (43%)	64 (56%)	χ^2: 3.132 (1); p = 0.053
Hypertension (*n* [%])	85 (43%)	40 (48%)	45 (40%)	χ^2: 1.489 (1); p = 0.141
Metabolic syndrome (*n* [%])	81 (41%)	38 (46%)	43 (38%)	χ^2: 1.290 (1); p = 0.161
Arterial stiffness (*n* [%])	61 (31%)	28 (34%)	33 (29%)	χ^2: 0.601 (1); p = 0.267
Smoking (*n* [%])	58 (29%)	33 (40%)	25 (22%)	χ^2: 7.350 (1); p < 0.01
Obesity (*n* [%])	40 (20%)	17 (20%)	23 (20%)	χ^2: 3.400 (2); p = 0.183

Table 3. Cardiovascular risk factors depending on socio-demographic, body mass index, lifestyle, and arterial stiffness characteristics

Factors	Hypertension			Dyslipidaemia			Metabolic syndrome		
	Males (*n* = 40; 48%)	Females (*n* = 45; 40%)	Overall (*n* = 85; 43%)	Males (*n* = 61; 74%)	Females (*n* = 79; 69%)	Overall (*n* = 140; 71%)	Males (*n* = 38; 46%)	Females (*n* = 43; 38%)	Overall (*n* = 81; 41%)
Socio-demographics									
Age categories (years)									
Under 30 (*n* [%])	0 (0%)	0 (0%)	0 (0%)	4 (7%)	3 (4%)	7 (5%)	0 (0%)	1 (2%)	1 (1%)
31–40 (*n* [%])	2 (5%)	4 (9%)	6 (7%)	6 (10%)	11 (14%)	17 (12%)	3 (8%)	5 (12%)	8 (10%)
41–50 (*n* [%]))	5 (13%)	7 (16%)	12 (14%)	12 (20%)	17 (22%)	29 (21%)	7 (18%)	3 (7%)	10 (12%)
51–60 (*n* [%])	17 (43%)	17 (38%)	34 (40%)	20 (33%)	28 (35%)	48 (34%)	16 (42%)	15 (35%)	31 (39%)
61–65 (*n* [%])	16 (40%)	17 (38%)	33 (39%)	19 (31%)	20 (25%)	39 (28%)	12 (32%)	19 (42%)	31 (38%)
Statistical inference	χ^2: 0.739 (3); p = 0.869			χ^2: 1.546 (4); p = 0.819			χ^2: 4.421 (4); p = 0.353		
Education									
< 6 years (*n* [%])	16 (41%)	24 (55%)	40 (48%)	21 (34%)	33 (42%)	54 (39%)	15 (40%)	26 (62%)	41 (51%)
6–12 years (*n* [%])	10 (26%)	8 (18%)	18 (22%)	16 (26%)	9 (12%)	25 (18%)	9 (24%)	5 (12%)	14 (18%)
> 12 years (*n* [%])	13 (33%)	12 (27%)	25 (31%)	24 (39%)	36 (42%)	60 (43%)	14 (37%)	11 (26%)	25 (31%)
Statistical inference	χ^2: 1.567 (2); p = 0.457			χ^2: 5.023 (2); p = 0.081			χ^2: 4.265 (2); p = 0.119		
Body mass index									
Normal weight (*n* [%])	2 (5%)	10 (22%)	12 (14%)	13 (21%)	29 (37%)	42 (30%)	2 (5%)	10 (23%)	12 (14%)
Overweight (*n* [%])	24 (60%)	21 (47%)	45 (53%)	33 (54%)	32 (41%)	65 (46%)	20 (53%)	19 (44%)	39 (42%)
Obesity (*n* [%])	14 (35%)	14 (31%)	28 (33%)	15 (25%)	18 (23%)	33 (24%)	16 (42%)	14 (33%)	30 (37%)
Statistical inference	χ^2: 5.257 (2); p = 0.072			χ^2: 4.137 (2); p = 0.126			χ^2: 5.203 (2); p = 0.074		
Lifestyle									
Tobacco consumption									
Non-smoking (*n* [%])	28 (70%)	42 (93%)	70 (82%)	38 (62%)	62 (78%)	100 (71%)	25 (66%)	38 (88%)	63 (78%)
Smoking (*n* [%])	12 (30%)	3 (7%)	15 (18%)	23 (38%)	17 (22%)	40 (29%)	13 (34%)	5 (12%)	18 (22%)
Statistical inference	χ^2: 7.933 (1); p = 0.005			χ^2: 4.419 (1); p = 0.028			χ^2: 5.952 (1); p = 0.014		
Physical activity									
Physically active (*n* [%])	22 (55%)	15 (33%)	37 (43.5%)	32 (53%)	35 (44%)	67 (48%)	20 (53%)	15 (35%)	35 (43%)
Physically inactive (*n* [%])	18 (45%)	30 (67%)	48 (56.5%)	29 (48%)	44 (56%)	73 (52%)	18 (47%)	28 (65%)	46 (57%)
Statistical inference	χ^2: 4.044 (1); p = 0.044			χ^2: 0.917 (1); p = 0.216			χ^2: 2.589 (1); p = 0.083		
Arterial stiffness									
Normal (*n* [%])	18 (46%)	21 (47%)	39 (46%)	34 (57%)	55 (70%)	39 (46%)	20 (53%)	19 (44%)	39 (48%)
≥ 10 m/s (*n* [%])	21 (54%)	24 (53%)	45 (54%)	26 (43%)	24 (30%)	45 (53%)	18 (47%)	24 (56%)	42 (52%)
Statistical inference	χ^2: 0.002 (1); p = 0.568			χ^2: 2.484 (1); p = 0.081			χ^2: 0.576 (1); p = 0.296		

Discussion

In this study, the prevalence of CVD risk factors was as follows: dyslipidaemia: 71%, physical inactivity: 51%, hypertension: 43%, MetS: 41%, arterial stiffness: 31%, smoking: 29%, and obesity: 20%.

Dyslipidaemia was established as any abnormal lipid profile or even the presence of lipid-lowering medication [3]. Indeed, dyslipidaemia is a broader concept, which exceeds a single lipid disorder [9]. Prevalence studies on dyslipidaemia in Portuguese populations are normally based on total cholesterol or on each lipid concentration separately [12, 13]. In this sense, among 40–76-year-old Portuguese patients from the same geographical area as our study referred to, hypercholesterolemia prevalence was 79.7% [12].

Physical inactivity was the second most prevalent CVD risk factor (51%). In a global CVD risk factors ranking, physical inactivity appears in the 4th position [14]. This discrepancy might be somehow explained by the use of different assessment methods between the studies. It is imperative to underline that a large body of evidence in this field is based on self-report measurements, which underestimate physical inactivity [10, 15]. Considering this, it is expected that objectively measured physical activity would re-arrange the CVD risk factors ranking.

In the present study, all waking minutes identified with ≥ 2020 counts/min were summed to derive moderate to vigorous physical activity and to classify participants as physically active [10]. This approach is a study limitation and has 2 consequences. Firstly, it justifies the median of 30 min/day in moderate to vigorous physical activity of the total sample. Secondly, it may have attenuated the prevalence of physical inactivity, once physical activity recommendations state that the minimum duration of a physical activity bout should last at least 10 consecutive minutes [11]. The dose-response effect of physical activity on cardiovascular health is supported by strong evidence, and numerous physiological pathways might explain this association [16]. For example, regular physical activity improves the lipid profile, lowering especially the triglycerides [17], and improves insulin sensitivity and glycaemic control, reducing the risk of metabolic diseases [18]. An acute aerobic physical activity bout augments cardiac output and the resultant shear stress forces stimulate the release of vasodilating substances such as nitric oxide and prostaglandins, diminishing blood pressure [19]. Additionally, the hypotensive effect gathered from chronic regular physical activity is linked with a reduction in oxidative stress and in low-grade inflammation [16]. Cardiovascular risk factors damage both the intima and media layers of arterial walls, impairing arterial compliance [6, 7], and, once more, regular physical activity is protective through its effect on each of the cardiovascular risk factors and also owing to its impact on cardiorespiratory fitness, a well-known parameter related to cardiovascular health [20]. Undeniably, all risk factors are somehow positively affected by physical activity, which justifies the importance of its promotion in terms of public health for the prevention of CVD.

The third most prevalent CVD risk factor was hypertension, and our data are in accordance with previous national (ca. 42%) [21] and international (ca. 30–45%) [22] reports based on the adult general population. In participants with hypertension, this particular risk factor was significantly higher among those who were simultaneously physically inactive. Indeed, as previously discussed, several physiological mechanisms are plausible to explain the pathways of physical activity action on blood pressure regulation, including, among others, improvement in endothelial function, diminishing chronic low-grade inflammatory state, improvement in the autonomic nervous system [16].

MetS results from a complex interplay between environmental and genetics factors and doubles the risk of developing CVD in 5–10 years' time [4]. Prevention of MetS onset is linked to a proper managing of lifestyle risk factors, highlighting physical activity [23]. Among our participants, 36% had MetS, and this is a higher prevalence compared with the global data (20–25%) [23]. The large variability in MetS prevalence might arise from the criteria used to define the condition [23]. In this sense, Santos and Barros [24] observed that within the same sample (from the same geographical area as ours), MetS varied between 26.4% and 41.4%, depending on the selected criteria.

Overall, we found that 31% of our sample presented a cfPWV ≥ 10 m/s stated by the Reference Values for Arterial Stiffness' Collaboration [6]. Between-study comparisons are difficult because data are almost inexistent. Nonetheless, the prevalence of cfPWV ≥ 10 m/s was 18.7% in 2542 Portuguese citizens aged between 18 and 96 years [25]. Raised arterial stiffness has been proposed as a pivotal CVD risk factor because it independently predicts both CVD and mortality [5]. Arterial stiffness is mainly determined by age and blood pressure [6], but other health conditions (dyslipidaemia, insulin resistance, obesity) and lifestyle risk factors (physical activity, sedentary time, diet, and tobacco consumption) exert effects that cannot be overlooked [5, 8]. Augmented arterial stiffness means that central arteries are losing its cushion capacity and, consequently, the blood flows faster, at higher pressures [7]. The arterial tree adapts to this flow pattern, and in terms of haemodynamic response, accelerated forward and backward waves are generated, intensifying the end-systolic pressure and reducing the coronary perfusion pressure [7]. The altered blood flow pattern in stiff arteries damages the heart, brain, and kidneys, and increases the risk of adverse events [6]. Early vascular aging means that the arteries are older compared with the chronological age. To some extent, it is expected in individuals with a constellation of risk factors [6]. Nevertheless, it is also possible to occur in apparently healthy people, free from traditional risk factors that are covered by the well-known cardiovascular risk algorithms [3]. Considering this, the additional predictive value of arterial stiffness as a cardiovascular biomarker appears to be relevant in the general population and must be confirmed in future studies.

The smoking prevalence was 29%, which is close to the recently reported 28.3% for a Portuguese sample [26]. We did not collect information on tobacco load or the time since tobacco consumption cessation, which constitutes a limitation of the study. Surprisingly, the prevalence of CVD risk factors was significantly higher in non-smokers than in smokers. Others have already published the same pattern [27] and there is no plausible explanation. We might guess that some of the non-smokers could be ex-smokers. As previously mentioned, the methodology used to assess smoking habits represents a limitation of this report and could at least partially explain these results. Additionally, it is eventually possible to speculate that the respondents may not have been totally honest when answering the smoking status question. If so, future studies might test for cotinine in order to verify the smoking status.

The prevalence of obesity (20%) was higher than previously reported for the Portuguese population [28]. Data from 2014 showed an obesity prevalence of 16.4%, which had risen by 1.2% since 2005 [28]. It is well known that obesity worsens most of the CVD risk factors [29], a reason why within participants with overweight or obesity, the prevalence of hypertension, dyslipidaemia, and MetS increases.

Taking into account the socio-demographic factors, the prevalence of hypertension, dyslipidaemia, and MetS increases with age, and is superior in males compared with females, as well as among those with the lowest educational level. These results are in agreement with the literature [22]. The educational level is the widest measure of the socioeconomic status, and in the last 40 years, an inverse association between education level and CVD prevalence has been consistently reported [30]. We can hypothesize that lower educational levels might be associated with worse lifestyle choices and with an eventually lower income, which reduce the level of information and health literacy, and limit the adoption of a healthy lifestyle owing to economic constraints.

Limitations

The sample was small and not representative of all geographical areas of the country, impeding generalizations for the entire Portuguese population. Seasonality influences the amount of daily physical activity and this was not considered in the analysis. The utilization of a specific cut-off point of moderate to vigorous physical activity might result in some misclassification of participants who were near this value; physical activity was considered as the sum of all minutes regardless the minimum duration of 10 minutes. In this study, the exclusion criteria could constitute a constraint for the generalization of the results. However, we intended to assess asymptomatic individuals who might be at risk of the initiation and progression of a pathology underlying ischemic cardiovascular diseases.

Conclusions

Our report shows a high prevalence of CVD risk factors within a sample of Portuguese citizens. Augmented arterial stiffening was observed in 1/3 of our sample, and physical inactivity was the second most prevalent risk factor, present in 51% of the sample.

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No author has any financial interest or received any financial benefit from this research.

Conflict of interest
The authors state no conflict of interest.

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A SINGLE TRAINING SESSION OF VISUAL CHOICE REACTION TIME AFTER MILD STROKE: A PROOF OF CONCEPT

original paper
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ABSTRACT
Purpose. Visual choice reaction time can be measured in reaching, which is an important task to investigate after stroke owing to its high clinical importance in activities of daily living. The study aim was to evaluate the visual choice reaction time during reaching tasks in the ipsilateral and contralateral spaces before and after a single training session of choice reaction time in patients after a mild stroke.
Methods. The cross-sectional study involved 7 individuals after a mild stroke. The visual choice reaction time was evaluated during reaching in the affected and unaffected sides in the ipsilateral and contralateral spaces. All individuals trained the choice reaction time during a functional reaching task in a single session. In the training, 6 circles were used in a randomized sequence in 5 blocks, with 10 stimuli per block, for a total of 50 repetitions.
Results. There was a significant reduction in the choice reaction time for the unaffected side in the ipsilateral space after training ($p = 0.041$). The other task conditions did not show a statistical difference, but a clinical relevance based on Cohen's *d* ($d > 0.60$).
Conclusions. A single training session can decrease the choice reaction time for the affected side during tasks in the ipsilateral space after a mild stroke.
Key words: stroke, choice reaction time, electromyography

Introduction

Visual choice reaction time (CRT) is measured with a set of stimuli and responses, with each stimulus being associated with a particular response [1, 2]. Stroke patients present a delay in CRT owing to slower motor responses [3–5], changes in muscular activation [6], and deficits in response selection [7], even in the absence of clinical motor deficits.

Visual CRT can be modified by the type of motor task (implicit or explicit), complexity of the task [3, 8], variability of the task (constant, blocked, and random tasks) [9], and training. Stewart et al. [10] show that a single training session can change the response time in a visual CRT task in stroke patients. In another study with a single session, the authors observed a slower performance in stroke patients than in control subjects in a condition with randomized tasks of high complexity [8].

Visual CRT can be measured in different activities, such as reaching, which is an important activity to investigate after stroke owing to its high clinical importance in activities of daily living [11]. Visual CRT response can be different between reaching tasks per-

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formed in the ipsilateral and contralateral spaces. Reaching in the contralateral space compared with that in the ipsilateral space has a longer latency, lower speed, and less precision [12]. Therefore, reaching tasks in the contralateral space are more complex [13], and other studies have verified that random practice in both spaces facilitates the consolidation of motor memory [14] and a reduction in reaction time [9]. However, the exact significance of this learning effect is unclear in individuals after stroke [15]. Therefore, a factor not yet investigated by the studies of reaching tasks is: Can a single training session of visual CRT modify the CRT values in both the regions of space?

Thus, the aim of the study was to evaluate visual CRT during reaching tasks in the ipsilateral and contralateral spaces before and after a single training session of CRT in patients after a mild stroke. The main hypothesis of this study was that the visual CRT during reaching would decrease after a single treatment session in both spaces.

Material and methods

Study design

A cross-sectional study was performed among individuals diagnosed with stroke. The data collection was carried out at the Laboratory of Biomechanics and Motor Control of Federal University of Triângulo Mineiro from March 2018 to February 2019.

Subjects

The eligibility criteria for participation in the study were: (i) mild stroke in the chronic stage, up to 1 year after ictus, confirmed by medical records and neuroimaging examinations; (ii) age > 18 years; (iii) a score of up to +1 (equivalent to minimum hypertonia) in the Modified Ashworth Scale (MAS) [16]; (iv) a score of > 30 on the Fugl-Meyer Scale (items related to upper limb function – mild stroke); (v) a Mini Mental State Examination (MMSE) score of ⩾ 20 points for individuals with 1–4 years of education, ≥ 25 points for individuals with 5–8 years of education, ≥ 26.5 points for individuals with 9–11 years of education, and ≥ 29 points for individuals with more than 11 years of education [17]; (vi) absence of other neurologic diseases, such traumatic brain injury, and any orthopaedic or rheumatic disorders that could interfere with the execution of the protocol.

Variable assessment

(a) MMSE: This scale was used to exclude individuals with cognitive impairment. It has a maximum score of 30 [18]. The cut-off points applied were those corresponding to the educational level of the participants [17].

(b) Fugl-Meyer Scale: It was used to investigate sensory-motor recovery. Only items related to upper limb function were considered, with a maximum score of 126 points [19].

(c) MAS: This scale served for the quantification of muscular tone. The scores range from 0 to 5 [20].

Outcome measures

For CRT evaluation, the individuals were seated in a chair with adjustable height, with their hips, knees, and ankles at 90° of flexion, their shoulders at 10–15° of flexion, their elbows at 75–90° of flexion, and their forearms pronated. To avoid compensatory movements, the trunk was stabilized at the 7th thoracic vertebra by using a chest brace. A monitor was placed in front of the individual at a distance dependent on the upper limb length, which was measured from acromion to the distal phalanx of the index finger, with a measuring tape. The seat height was adjusted to 100% of the lower limb length, which was measured from the lateral knee joint to the floor in a straight line with the subject standing barefoot. The centre of the monitor height was adjusted to 75% of the subject's shoulder height, which was defined as the distance from the shoulder marker to the floor with the participant sitting in the standardized position (Figure 1A). The individual had to reach in the ipsilateral or contralateral spaces in response to the visual stimulus, as quickly and accurately as possible, and return to the anatomic initial position at the end. The visual stimulus, represented by a white circle, lasted 5 seconds and could appear at 5, 6, 7, 8, or 9 seconds in a randomized sequence. The circles used for the evaluation were only circles 3 and 4 (Figure 1B).

The electromyographic (EMG) signal of the anterior deltoid was used to determine the onset of the muscle response analysed. The EMG signals were recorded with a Delsys Trigno TM® wireless telemetry sensor at 2000 Hz, in accordance with the Surface Electromyography for Non-Invasive Assessment of Muscles protocol [21]. A photodiode was applied to synchronize the EMG signal with the visual stimulus.

CRT was calculated in milliseconds by the difference between the photodiode signal and EMG activ-

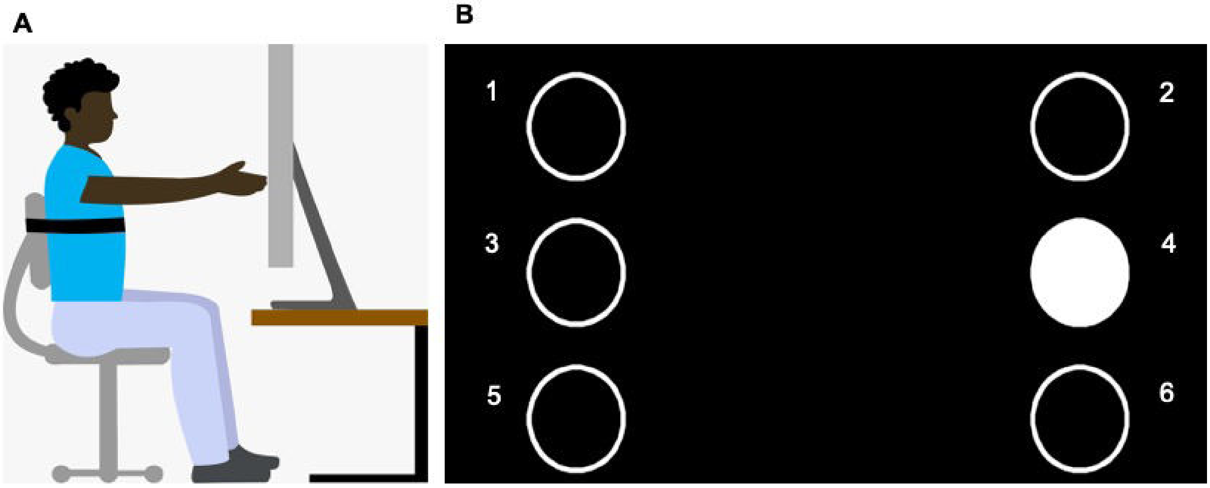


Figure 1. (A) The individual's position during the evaluation and the choice reaction time training session (B) representation of a visual stimulus on the screen

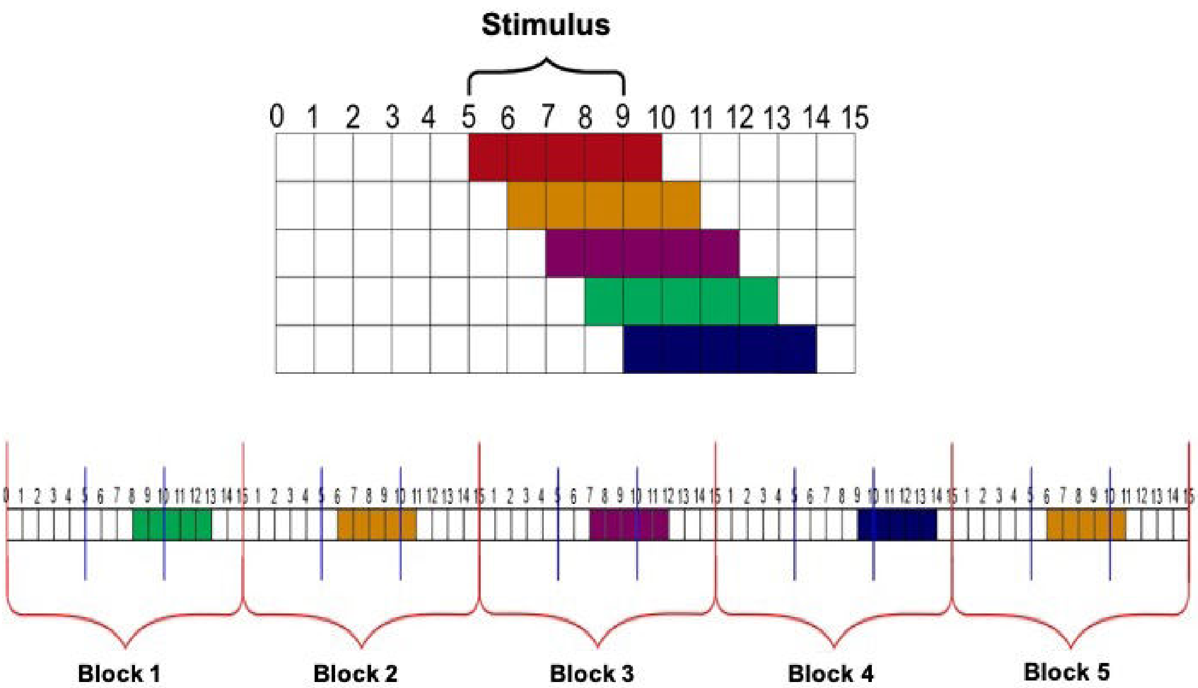


Figure 2. Configuration of choice reaction time training

ity in 4 reaching tasks: (1) reaching with the affected side in the ipsilateral space; (2) reaching with the unaffected side in the ipsilateral space; (3) reaching with the affected side in the contralateral space; and (4) reaching with the unaffected side in the contralateral space.

All of the assessment tools were administered by a physiotherapist. All participants included in the evaluation participated in a weekly rehabilitation (physical therapy and occupational therapy) programme in accordance with the American guidelines for rehabilitation in stroke patients [22].

Interventions

Each individual had to reach in the ipsilateral or contralateral spaces in response to the visual stimulus, as quickly and accurately as possible, 5 minutes after CRT evaluation. In the training, all 6 circles were used in a randomized sequence in 5 blocks, with 10 stimuli per block, for a total of 50 repetitions [23] (Figure 2). The training was conducted with both upper limbs in a single session. After the training, the individual was reassessed by the same CRT evaluation.

Sample size

The sample size was calculated to match the primary outcome with sample size estimation. On the basis of treatment effect change and 1.10 of effect size, with a fixed alpha error of 0.05 and beta error of 0.20, 7 patients constituted the necessary sample. The sample size calculation was performed with the G*Power 3.1.3 software.

Statistical methods

Descriptive statistics were used for sample characterization. The CRT variables presented a normal distribution (Shapiro-Wilk test), and Student's *t*-test for dependent variables (CRT) served to compare the pre- and post-intervention results for both sides in each space. Pearson's correlation test was applied used to assess the associations between the CRT on the affected and unaffected sides, as well as the MMSE, MAS, and Fugl-Meyer scores. The associations were considered significant at the value of $p < 0.05$. In addition, Cohen's d test was used to analyse the effect size and clinical relevance ($d < 0.5$, small clinical relevance; d of 0.5–0.79, moderate clinical relevance; $d > 0.8$, large clinical relevance) [24], and kurtosis (k) analysis was performed to assess data variability. The data were analysed with the IBM SPSS Statistics® version 21 and Prism 7 software.

Ethical approval

The research related to human use has complied with all the relevant national regulations and institutional policies, has followed the tenets of the Declaration of Helsinki, and has been approved by the authors' institutional review board.

Informed consent

Informed consent has been obtained from all individuals included in this study.

Results

A total of 20 patients were recruited, and 7 were included in this study (Figure 3).

The convenience sample was composed of 7 individuals with stroke (Table 1).

There was a significant reduction in CRT for the unaffected side in the ipsilateral space after training (mean difference [MD]: –0.048; CI: –0.096 to –0.011; $p = 0.041$). There was no significant difference in CRT for the affected side in the ipsilateral space after train-

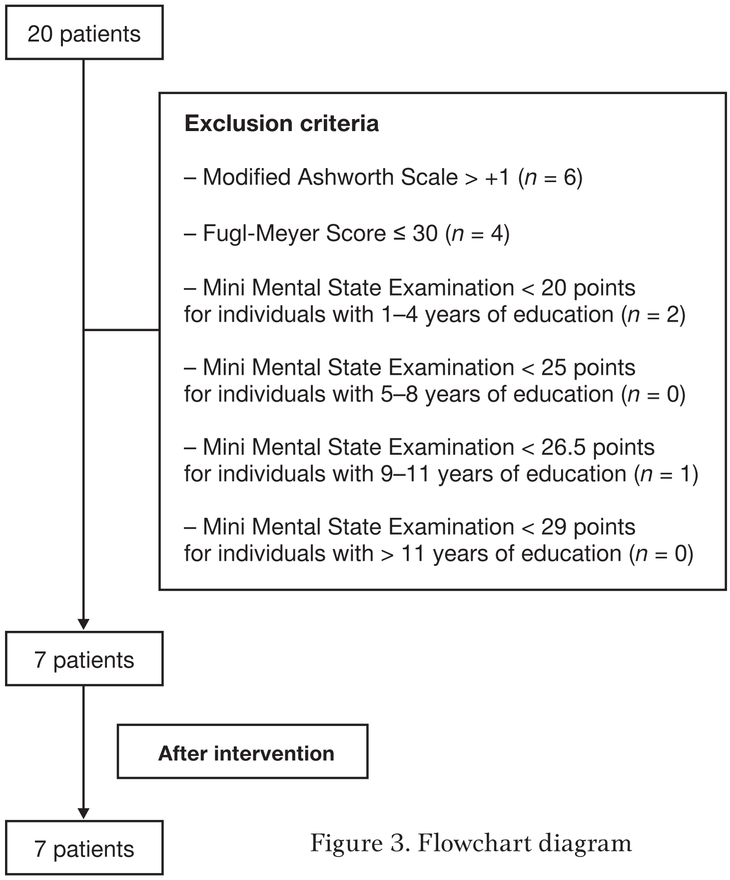
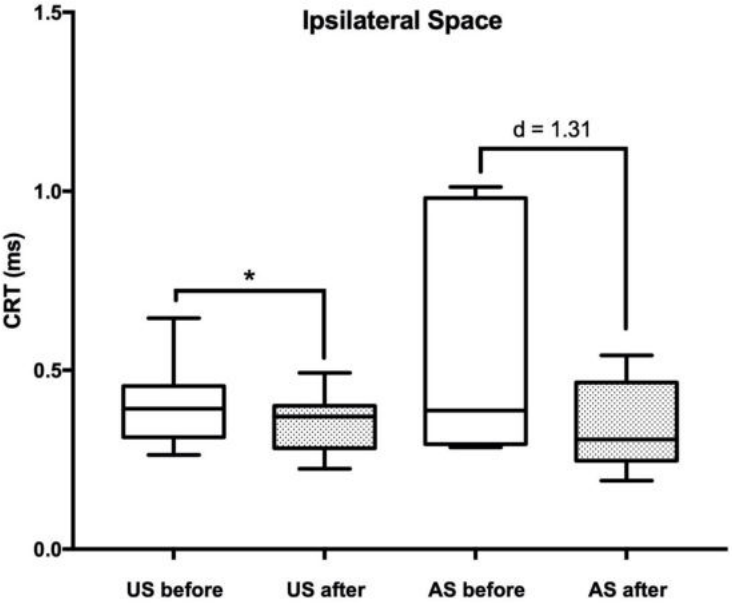


Figure 3. Flowchart diagram

Table 1. Experimental group characteristics

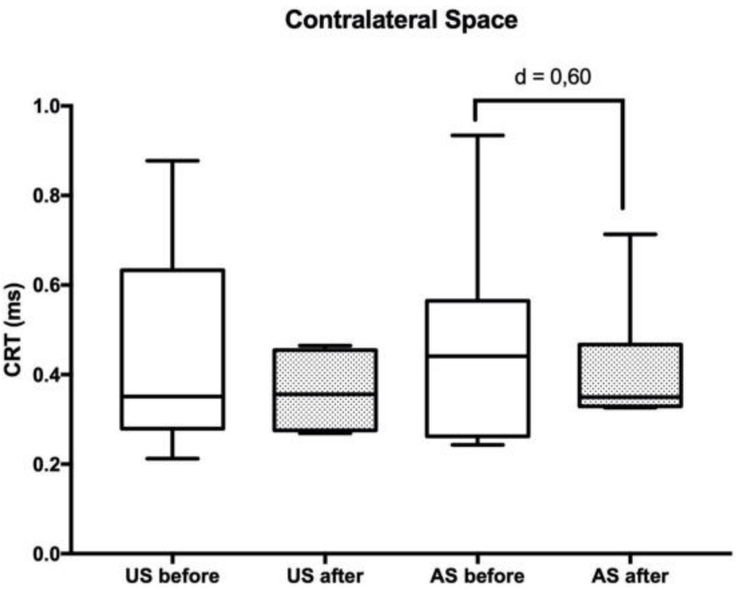
Variables	Value
Gender[1]	
Female	2
Male	5
Age[2] (years)	63.14 ± 3.48
Type of stroke[1]	
Ischemic	6
Haemorrhagic	1
Time of stroke[2] (days)	224.43 ± 111.25
Upper limb affected[1]	
Right	3
Left	4
Mini Mental State Examination[2]	23.71 ± 5.17
Fugl-Meyer Scale[2]	121.14 ± 8.04
Ashworth[3] (scores: 1/0)	2/5

1 – number of participants
2 – mean ± standard deviation
3 – ratio between the number of participants with score 1 and 0



CRT – choice reaction time
US – unaffected side
AS – affected side
* Significant reduction in CRT for the unaffected side in the ipsilateral space after training (p = 0.041)

Figure 4. Choice reaction time before and after training for the affected and unaffected sides in the ipsilateral space



CRT – choice reaction time
US – unaffected side
AS – affected side

Figure 5. Choice reaction time before and after training for the affected and unaffected sides in the contralateral space

ing (MD: –0.239; CI: –0.510 to 0.03; p = 0.074) (Figure 4), but Cohen's d test showed high clinical relevance (d = 1.31) in this condition. CRT variability decreased on both sides in the ipsilateral space: k_{before} = 2.19 and k_{after} = 0.26 for the unaffected side; k_{before} = –1.98 and k_{after} = –0.29 for the affected side.

There was no significant difference in CRT values for both limbs in the contralateral space (MD: 0.04; CI: –0.06 to 0.159; p = 0.310) and the ipsilateral space (MD: –0.07; CI: –0.248 to 0.104; p = 0.347) (Figure 5). Cohen's d test showed moderate clinical relevance (d = 0.60) for the reduction in CRT on the affected side in the contralateral space. CRT variability values for the unaffected side were k_{before} = 1.16 and k_{after} = –2.55, and the variability decreased on the affected side in the contralateral space (k_{before} = 4.30 and k_{after} = 2.11).

Discussion

The main findings of the present study were as follows: (1) In the ipsilateral space, differences in the visual CRT values of the unaffected side were observed before and after training; although the differences were not statistically significant, a high clinical relevance was determined in this condition. (2) In the contralateral space, a moderate clinical relevance was indicated in the visual CRT values of the affected and unaffected sides.

De Paiva Silva et al. [25] highlighted that movement direction influenced both movement planning and execution. Reaching over the midline and the presence of a choice increased the complexity of the task. Such complexity needs to be considered during the evaluation and training of individuals after stroke [26].

Why did the visual CRT values for the unaffected limb decrease after a single session in the ipsilateral space but not in the contralateral space? The medians of the visual CRT for both sides were similar, but there was greater variability before training for the unaffected limb. After visual CRT treatment, the variability of the visual CRT values decreased, which could contribute to the high clinical relevance. The visual CRT for the unaffected limbs can be similar to that in healthy limbs despite the number of non-crossing motor fibres in the motor cortex [27]. The visual CRT reduction can be explained by enhanced cognitive activity during random practice, higher engagement in inter-task elaborative processing, and the need to reconstruct an action plan after each trial [28].

A single training session cannot be sufficient to reduce visual CRT in complex tasks, such as reaching in the contralateral space. In our study, visual CRT was bigger during reaching in the contralateral space, with higher variability. This finding supports the hypothesis that contralateral movements are more complex and thus lead to longer CRTs owing to the greater need for spatial orientation, body scheme development, and bilateral coordination [29–31].

Klapp [32] suggested that planning took longer for more complex movements, which is reflected in CRT. Therefore, it seems impossible to change visual CRT in the contralateral space during explicit tasks with only a single session [32]; however, in another study that used a single session, the authors observed that individuals were able to learn an implicit motor task, with a decrease in reaction time [8]. After practice, implicit motor learning is evidenced by the fact that participants generally respond significantly faster to sequenced stimuli than to randomly presented ones, without being able to explicitly recall or recognize this learned sequence [33]. The length and intensity of the treatments reported in the literature were not defined [13]. Studies have shown that one session can promote improvement in the motor system. For example, high-intensity training can increase motor learning and prehension ability after stroke [34].

Considering these interesting findings in this proof of concept, we emphasize the importance of a large sample size and a visual CRT test after 24 hours of training. This study brings an important contribution to research on rehabilitation after stroke, which may infer that a random and distributed single training session reduces visual CRT in the ipsilateral space at the unaffected side, but the data of clinical relevance showed also visual CRT reduction in the contralateral space at the affected side. These findings must be reinforced through multicentre randomized clinical trials to explore not only the performance, but also the learning effects after visual CRT training.

Conclusions

Visual CRT decreases on the unaffected side in ipsilateral space after a single CRT training session in individuals after a mild stroke.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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EFFECT OF STRESS ON HAND MOVEMENT IN A LABORATORY SETTING AMONG HIGH SCHOOL STUDENTS: PRELIMINARY RESEARCH

original paper
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ABSTRACT
Purpose. The purpose of this study was to investigate the effect of stress on movement before and after a computer application-based simulated stress task.
Methods. Differences in the movement of participants were examined by measuring movement quality described by wrist accumulated distance, velocity, acceleration, jerk, and smoothness. Ten high school students performed 3 horizontal and vertical hand circling movements before and after a simulated concentration-based stress task. Blood pressure was measured, and a saliva sample was collected before and after the stress test execution. The participants were instructed to take a 10-minute relaxation period, perform 3 horizontal and vertical circling movements, a 20-minute stress task, and then perform 3 horizontal and vertical movements.
Results. There were significant differences between before- and after-stress-task levels of cortisol ($p < 0.05$), heart rate ($p < 0.01$), smoothness ($p < 0.01$), and jerk movements ($p < 0.05$) in the vertical plane. The stress-related variables were lower after the relaxation phase than the stress task. Likewise, movements were smoother and had less jerk in the vertical plane after relaxation.
Conclusions. This study indicates that stress may affect hand movement quality in the vertical plane. Therefore, we recommend that any movement behaviour adaptive therapy should focus on movements in the vertical plane.
Key words: movement, health behaviour, stress, Laban analysis, behaviour

Introduction

Korea is known for its high technology and rapid development; however, this came with a price of growing social issues, such as mental health problems (depression, anxiety, learning disabilities, and aggressive behaviour). Furthermore, as a result of the fast economic growth, the Korean society has become ultra-competitive in many social arenas, especially the academic sector, which has a high suicidal rate [1]. According to the Organization for Economic Co-operation and Development [2], Korea produces high-ranking students in mathematics and science. However, its educational system is reported to be one of the most significant stressors of depression and suicide in youths (7.8 per 100,000 people) [1]. Academic stress at high school is elevated owing to the difficulties of entrance into a high-ranking university, making career choices, student's

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low academic achievement, amount of academic work, and a lack of rest [1]. The pressure to perform successfully at school is a heavy burden for adolescents, as there is a strong Korean culture of having high expectations and an aspiration to accomplish high academic scores [3]. More importantly, this time of high stress and consequently poor academic performance is reported to be a major trigger for depression, anxiety, and suicidal ideation [3, 4].

With the high importance that students place on academic achievement to get into a good university, engagement in class and high levels of concentration are reported to be strong predictors of academic achievement [5]. The authors conclude that for engagement to occur, concentration is a critical factor, and if stress exists, it can have a negative effect on concentration levels. Similarly, Lee [6] suggests that educational interventions should focus on improving student concentration, whereas other research states that maintaining a stress-free environment is vital for effective academic performance [7].

In this study, we were interested in how stress could affect movement and how movement could affect stress. Our hypothesis was that movement could affect stress, as in the recent findings explained by Shafir [8] that movement could regulate emotion, i.e. motor behaviour, such as engaging specific facial expressions, posture, and whole-body movements. We developed a horizontal and vertical plane hand circling movement as we were interested in how stress affected movement in both the horizontal and vertical planes. Upward movements have been associated with emotions such as joy, surprise, and admiration [9]. Moreover, there is an increase in emerging research describing the ability of motion capture systems to quantify emotions by analysing certain movement qualities [9]. These automatic emotion classifying systems are based on the movement qualities and posture positions, such as an open and closed posture, which are associated with different emotional states [9]. The movement using the upper body segments was selected because breathing is known to affect stress levels and therefore would influence the movement of the scapula and arms [10].

Lefter et al. [11] have developed and investigated novel methods of measuring stress from human-human interactions by analysing audio-visual recordings. Moreover, automatic methods were developed to recognize stress from semantic messages, such as spoken words for speech and meaningful gestures, and stress conveyance by the modulation of speech intonation and the speed and rhythm of gestures. A distinct advantage of the methods developed by Lefter et al. [11] for measuring stress is that they are non-invasive and can be applied in numerous situations. Thus, in this study, we hypothesized that stress could affect movement characteristics (movement distance and kinematics) and movement quality (smoothness). With this hypothesis, our ultimate aim is to understand how stress during concentration tasks alters movement characteristics. By knowing how movement might be affected by stress, we plan to develop and test the bidirectional relationship between movement behavioural correction methods and their ability to reduce stress in additional studies.

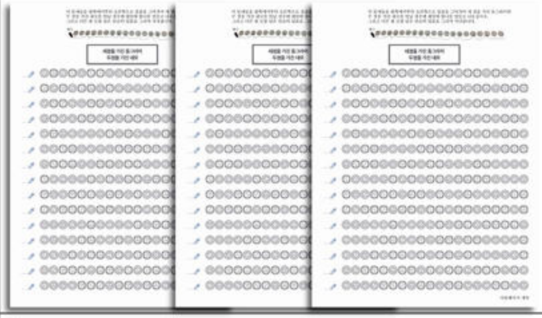
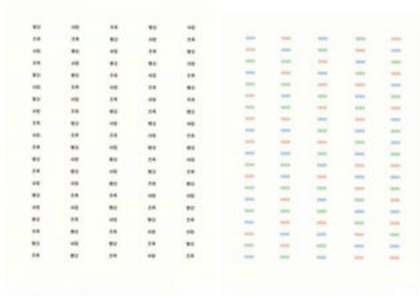
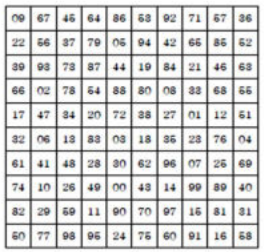
Material and methods

Participants

The group of participants, high school students, included a total number of 10 people (mean age: 15.7 ± 0.48 years, mean height: 1.7 ± 0.08 m, mean weight: 68.3 ± 13.2 kg) recruited from a local high school. The recruitment procedure was public and a poster was placed on the high school notice board after permission was obtained from the school.

Stress task development

Common stress tasks, such as the Trier Social Stress Test and the Sing-a-Song Stress Test, were deemed unsuitable for high school students; as many stress tasks are commonly criticized for their lack of potency as a stressor [12], we developed our own one. Upon the advice of a group of 5 local psychology experts (content validity ratio > 0.99 for n = 5) [13], we developed our stress task (total: 20 minutes) by mixing and editing the contents of 3 cognitive tasks (that were deemed essential by all experts questioned): the Korean FAIR concentration test (10 minutes, based on Gnambs and Freund [14], reliability ranging 0.9–0.94 [15]); the Korean Stroop Test (3 minutes, reliability Cronbach's alpha: 0.78 [16]); and filling in a 10 × 10 concentration grid task (7 minutes, 1-week test-retest reliability: 0.79 [17]). These 3 tests were selected to stimulate factors that are needed in an academic setting, i.e. concentration, attention, and selective attention. The total time for the stress task was 20 minutes as Hellhammer and Schubert [18] have reported that it takes 10–20 minutes for the saliva cortisol level to reach a maximum. Furthermore, we altered these tests and converted them from the standard paper format to a format that could be used on an iPad [19] (details are shown in Figure 1).

Test	Actual Test	Altered for ICT version	Contents
FAIR Concentration Test			• We created 6 patterns based on existing checklists and adjust the number of questions to control time and difficulty for high school student
Stroop Test			• We added more rows (20*5) and rearranged the colors, icons, etc. to control the level of difficulty. • We created 7 A4 page size worksheets based on the existing paper form.
10x10 Grid			• We created a gird with numbers increasing in size to increase the difficulty • We started at 10x10, 15x15, then 20x20.

ICT – information and communication technologies

Figure 1. Conversion of tests form paper format to computer application-based format

Testing procedure

The experimental setup and procedure had the following steps:

1. *Participants' consent and exclusion criteria.* After an introduction to the test procedure and obtaining the participants', parents', or guardians' consent, the study proceeded. To ensure that all participants had no high stakes examinations close to the time of testing, the recruitment and testing took place early in the academic school calendar. Furthermore, prior to arrival, all participants were instructed not to have any caffeinated or acidic drinks within up to 24 hours before participating in the study.

2. *General stress questionnaire.* The participants filled in a general stress questionnaire [20], which consisted of 21 questions and focused on their expectations, internal feelings, and expression of the stress response. The internal consistency, Cronbach's α, of the academic stress scale ranged 0.83–0.89 [20]. The stress questionnaire was used to ensure the homogeneity of the participants. One of the 11 participants' data had to be removed because the motion capture data were corrupt.

3. *Preparation and physiological data collection phase.* Before the stress task was performed, the participants had their blood pressure measured (MDF Instruments, USA) and provided a sample of saliva (5 ml) (JMBio Care, Republic of Korea). Then, each subject changed into an outfit required for better data acquisition (tight-fitting top, spandex shorts) and was equipped with a heart rate monitor (Polar, Electro Oy, Kempele, Finland) chest strap.

4. *Relaxing phase.* The goal of the relaxation phase was to create a condition in which the participants would be able to relax. The students were instructed to go to a designated area (enclosed for privacy) to relax sitting with their eyes closed on a large bean-bag; during this relaxing 10-minute period, the participants' heart rate was continuously monitored [21].

5. *Motion capture data acquisition and stress task phase.* The participants were fitted with 11 reflective markers (25 mm) on the upper body (left and right shoulder, elbow, wrist, forehead, back of the head, and the sternum). Each student was instructed to perform a T-pose static position followed by 2 types of dynamic arm circling movements (Figure 2); first, in the horizontal (transverse) plane, and then in the vertical (frontal) plane. Each movement was repeated 3 times. For the horizontal movement, the left and right hand began in the anatomical position (standing straight with the palms of the hands facing anteriorly), moving in the anterior direction in the coronal plane, then performing a lateral movement (Figure 2), and returning to the anatomical position. For the vertical movement, the left and right hand began in the anatomical position, moving in the superior direction in the frontal plane, then performing a lateral movement (Figure 2), and returning to the anatomical position. The students were instructed to perform these 2 circling movements as large, smooth, and relaxed as possible, with no audio stimulation for the timing. After that, the subjects performed a stress task, sitting down at the desk. The stress task consisted of 10 minutes of the FAIR concentration test, 3 minutes of the Stroop Test, and 7 minutes of filling in a 10 × 10 grid. To make a more stress-

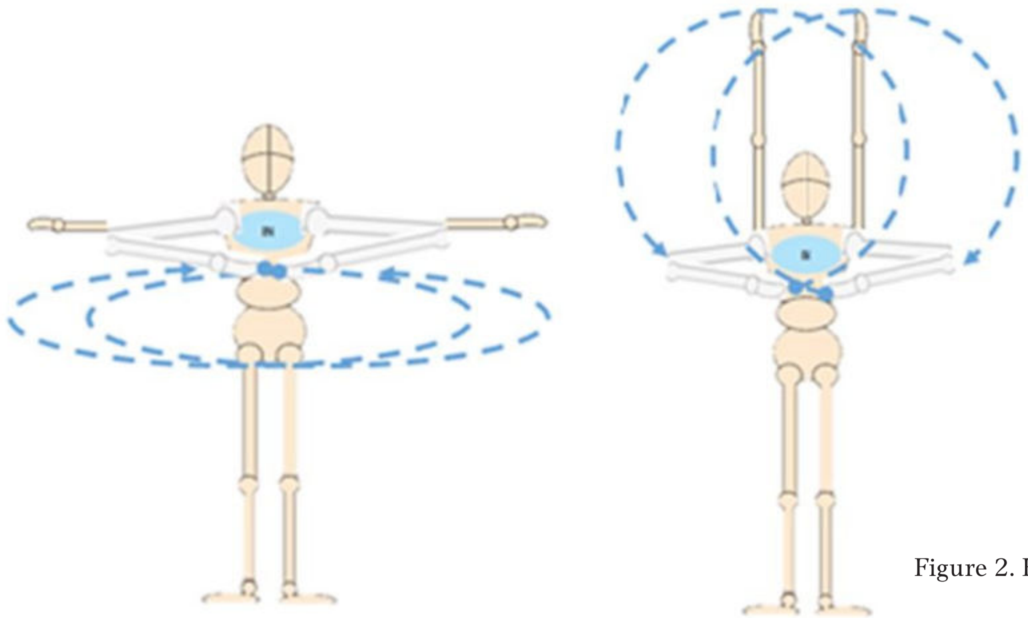


Figure 2. Horizontal and vertical arm circling motion

ful environment, each student was instructed that their parents or guardians were watching and that they were to do their best. After the stress task, the participants were asked to perform the same circling arm movements in the horizontal (transverse) plane and in the vertical (frontal) plane as before the stress task. Directly after that, the students were requested to provide a saliva sample and had their blood pressure measured.

Equipment and data processing

Kinematic data were recorded with a 3D tracking system (OptiTrack, USA) which consisted of 12 high-resolution cameras (Prime 41, USA). The positional data of reflective markers were recorded at 60 Hz by the OptiTrack software Motive (version 1.10.3). The data were post-processed: labelled and noise and jitter trajectories were eliminated. Afterward, the data were exported to the C3D file format for further analysis in Visual3D (C-Motion, USA). Kinematic data were filtered with a 2^{nd} order zero-lag low-pass filter (cut-off frequency of 8 Hz), which was determined by applying a fast Fourier transform. The data are available from the corresponding author upon request.

Movement features and physiological measures extraction

In order to perform the movement analysis and explore how stress affected movement, we calculated and extracted movement features from the position of right and left wrist markers changing through time: accumulated distance, smoothness, and jerkiness. The accumulated distance was calculated as a cumulative sum of the absolute values of the displacements, the total distance travelled by the marker of the left and right wrist. Smoothness was defined as the ratio between velocity and acceleration of the normalized and averaged motion capture data. ‘Smoothness value’ is the value in the range [0,1] (the higher the value, the higher the smoothness). Jerkiness was calculated as the rate of change of acceleration, that is, the derivative of acceleration over time, and as such it is the second derivative of velocity, or the third derivative of position. The jerk is the rate of change of acceleration and its units are meters per second cubed. The movement features were computed by using a Motion Capture Toolbox in MATLAB for computational analysis of movement data.

For physiological data, heart rate (bpm), systolic blood pressure (mm Hg), diastolic blood pressure (mm Hg), and cortisol concentration (μg/dl) were recorded. This study detailed various physiological factors to strengthen the validity of the stress level measurement owing to the differences in stress depending on personality types. Heart rate data were recorded with a Polar sensor (RS400, Electro Oy, Kempele, Finland) at a frequency of 100 Hz during the entire testing period. Blood pressure was measured manually by the same research assistant, who was specifically trained for internal consistency. Salvia samples were taken by the same research assistant and stored in an icebox, which was delivered on the next day to an independent company (JMBio Care, Republic of Korea) for analysis.

Statistical methods

The statistical analysis was carried out by using the SPSS software (version 23.0). The before- and after-task data were calculated; then, a paired *t*-test was used to investigate if there were statistical differences, with a significance level of $p < 0.05$. To further investigate the meaning of the significant differences, we followed with the recommendations by Dunlap et al. [22] for calculating the effect size of the paired *t*-test to see how large the significant differences were. On the basis of Cohen’s effect size recommendations, the d value of 0.2–0.5 stood for small effect size, d of 0.5–0.8 for medium effect size, and $d > 0.8$ for large effect size [23]. Owing to the difficulty of recruiting, we had 10 participants and so to check the statistical power, we performed a post-hoc power analysis using the G*Power software, with the sample size of 10 and the alpha level of 0.05, which resulted in a power of 0.839, deemed an acceptable power according to Cohen [23].

Ethical approval

The research related to human use has complied with all the relevant national regulations and institutional policies, has followed the tenets of the Declaration of Helsinki, and has been approved by the Pusan National University Institutional Review Board (PNU# 2017_33_HR).

Informed consent

Informed consent has been obtained from all individuals included in this study and from their legal guardians.

Results

The paired *t*-test showed significant differences between the status before and after the stress task for the systolic and diastolic blood pressure. Among the physiological variables, there were significant differences with medium to strong effect sizes between the levels of cortisol ($t = 2.35$, $p < 0.04$, $d = 0.61$) and heart rate ($t = 3.93$, $p < 0.003$, $d = 0.53$) before and after the stress task. However, there were no significant differences in blood pressure (Table 1).

Among the kinematic variables from the motion data, smoothness and jerkiness showed statistical differences only for the vertical hand circling movement. Among the kinematic data, there were significant differences with medium to strong effect sizes for smoothness (left wrist: $p < 0.008$, $d = 0.67$; right wrist: $p < 0.042$, $d = 0.41$) and jerk (left wrist: $p < 0.023$, $d = 0.82$; right wrist: not significant) during the vertical hand circling movement. No significant differences were reported for any of the variables, such as accumulated distance, velocity, acceleration, smoothness, or jerk for the horizontal hand circling movement between the status before and after the stress task (Table 2).

Table 1. Comparison of physiological data between the status before and after the stress task

Parameter	Before	After	*p*	Effect size (*d*)
Blood pressure – systolic (mm Hg)	117.21 ± 7.60	116.62 ± 10.70	0.71	NA
Blood pressure – diastolic (mm Hg)	73.20 ± 6.12	72.40 ± 9.27	0.62	NA
Cortisol (μg/l)	3.30 ± 0.81	4.30 ± 1.61	< 0.04*	0.61
Heart rate (bpm)	76.50 ± 8.87	81.20 ± 9.40	< 0.003**	0.53

Values are expressed as mean ± standard deviation.
NA – not applicable
* $p < 0.05$, ** $p < 0.01$

Table 2. Comparison of kinematic and movement quality data between the status before and after the stress task

Parameter	Horizontal circling		Vertical circling	
	Left wrist	Right wrist	Left wrist	Right wrist
Accumulated distance (m)				
Before	4.79 ± 1.57	4.65 ± 1.82	4.03 ± 1.88	4.99 ± 1.51
After	4.33 ± 1.61	4.11 ± 1.38	5.32 ± 1.73	4.47 ± 1.34
p	0.609	0.502	0.160	0.571
Velocity (m/s)				
Before	0.0361 ± 0.04	0.0291 ± 0.03	0.006 ± 0.01	0.010 ± 0.01
After	0.0349 ± 0.04	0.0339 ± 0.03	0.020 ± 0.02	0.0171 ± 0.02
p	0.947	0.782	0.108	0.065
Acceleration (m/s^2)				
Before	0.0523 ± 0.05	0.0343 ± 0.04	0.0287 ± 0.03	0.0359 ± 0.04
After	0.0833 ± 0.15	0.0793 ± 0.14	0.0568 ± 0.09	0.0543 ± 0.08
p	0.562	0.373	0.333	0.230
Smoothness				
Before	0.22 ± 0.025	0.23 ± 0.021	0.27 ± 0.045	0.27 ± 0.049
After	0.22 ± 0.028	0.23 ± 0.030	0.24 ± 0.032	0.25 ± 0.027
p	0.939	0.871	0.008**	0.042*
Effect size			0.67	0.41
Jerk (m/s^3)				
Before	30.71 ± 8.66	27.33 ± 7.99	24.53 ± 8.89	25.07 ± 9.26
After	34.61 ± 12.36	30.75 ± 8.34	31.87 ± 9.61	29.09 ± 9.91
p	0.245	0.167	0.023*	0.161
Effect size			0.82	

Values are expressed as mean ± standard deviation.
NA – not applicable
* $p < 0.05$, ** $p < 0.01$

Discussion

In summary, this study demonstrates how a simulated stress task may influence the movement quality among high school students in a laboratory setting. The kinematic results in this study show that a stress task can affect the smoothness and the jerk of the movement. Interestingly, before the stress task was employed, the movements could be described as more efficient, as the movement distance tended to be reduced, i.e. less mechanical work was performed; however, this was not statistically significant. Similar to skill levels in sports and dance, more skilled athletes and dancers' movements are reported to be smoother and have less jerk (golf [24], dancing [25]). Likewise, the participants' upward hand circling movements were smoother after the relaxation period at the start, and had lower jerk values than after the stress task. Furthermore, high jerk values in the movement have been linked with various health issues, such as Parkinson's disease [26] and poor gait function [27].

Among the physiological data, cortisol level and heart rate indicate that the participants' stress level increased as a result of our stress task as both parameters increased significantly (moderate to strong effect size) [28]. There was not a significant effect of the stress task on the systolic or diastolic blood pressure. There seem to be some contradictions in the published research as some of the stress-related studies show an increase in the blood pressure [29], whereas some present no significant effects [30]. In an interesting study, the authors demonstrated no significant differences between the blood pressure and heart rate between stress and control conditions. Remarkably, just performing one 30-minute session of hatha yoga was reported to significantly accelerate the recovery of blood pressure and heart rate after doing a paced auditory serial addition test as a psychological stress task [31]. Moreover, as stress is known to affect breathing patterns and potentially induce different emotional states [32], we hypothesized that stress could be reduced by controlling breathing, which might decrease muscle tension and thus help the movement to become more smooth.

Another study, which measured heart rate variability and blood pressure during a mental stress task in the course of computer work [33], showed that there were significant differences between the heart rate variability during rest and stress task. Contradictory to our study, Hjortskov et al. [33] observed differences in blood pressure during different testing periods as a response to combined physical and mental workloads, as well as during and after periods of rest. Our study did not reveal any significant variations in the blood pressure but there was an overall lowering of systolic blood pressure after the stress task, which can be viewed positively in an educational setting as it indicates that the participants were more relaxed as soon as the stress task was finished, and is linked to better memory function [34]. A study investigating the effect that conflict had on cortisol levels reported a rapid reduction of cortisol level after the conflict was terminated [35], which might explain the lack of significant blood pressure differences between the status before and after the stress task. However, at this moment, we are unsure why the stress task affected the cortisol levels and heart rate, but not the systolic or diastolic blood pressure. Further studies should be carried out to investigate the relationship between different stressors and individual responses across varied age groups, i.e. from teenagers to older adults.

It is important to mention the various limitations of this study. Creating a stress task that is not too severe and therefore allows to obtain an institutional review board approval is difficult [12]. Previous research has employed several tests, which have a very narrow application, such as the Trier Social Stress Test [36] or Sing-a-Song Stress Test [37]. In the implementation of these tests, research highlights the large variation in the psychological and physiological effects of individual participants' responses as a limitation of their usage [36]. In this study, we were focused on investigating the effect of academic type stress situations which require concentration/attention during the stress task, so these existing tests (Trier Social Stress Test and Sing-a-Song Stress Test) would not have been suitable. The present study can be perceived as a preliminary investigation of the use of analysing movement quality characteristics to detect stress early; by understanding the dimensions in which movement is effected, a stress relief procedure may be developed engaging movement in the affected dimensions. The data in this study show that the stress task affected the movement pattern in the vertical plane but did not affect it in the horizontal plane; therefore, we could develop a movement-based intervention focusing on movement in the vertical (frontal) plane to help reduce stress. In psychological research on removing a nervous habit and tics [38], the majority of nervous movements tended to be upward movements of the limbs, i.e. shoulder jerking, as well as nail-biting, head jerking, and eyelash plucking. To remove these habits and tics, the authors recommended and tested their theory of behavioural pattern opposite corrective exercises, such as depressing the shoulders, tensing of the neck, holding the hands and shoulders down. Interestingly, these pattern opposite exercises were reported to be effective in 11 of the 12 participants of the study. We believe that the correlations between the physiological states and movement characteristics and movement quality data may be helpful to establish more detailed automated behavioural analysis techniques for an infield high school classroom-based study.

A major limitation was the difficulty of recruiting more than 10 students to participate in the study. Even though the Institutional Review Board consent was received from the University Hospital, it was very problematic to acquire the 3 parties involved (the school principal, the students, and their parents/guardians) to agree to partake in the research. As the majority of high school students in Korea attend after-school institutes for additional study and classes up until 10:00 or 11:00 p.m. during school days, all the testing had to be carried out during the weekend, which made the students even more resistant to participate. We had planned to test 30 individuals but even after recruiting students for 3 months, we were only able to recruit 10 subjects.

As stress affects both physiological and movement characteristics and movement quality, advanced computer vision techniques may be developed to analyse these so that they can be applied in stressful environments, such as schools, hospitals, flight control centres, where the tracking of the patrons' stress level would be useful for improving quality of care and provide continuous monitoring of the psychological status. Therefore, non-invasive behaviour-based stress analysis can be a very useful method of detecting people's stress-based behaviours early. On the basis of the relationship between stress and behaviour, Lefter et al. [11] are developing a system that can recognize stress through the analysis of semantics and modulation of speech and associated gestures. They highlight the difficulty of measuring stress through behaviour as it is conveyed by a large variety of combinations of various communicative acts. Furthermore, the authors suggest that it is easy to misinterpret a behaviour without considering the overall gestures and other nonverbal cues such as postures, facial expressions, and body language.

Conclusions

This study shows that our stress task affected the stress level and movement quality in male and female high school students. Secondly, we indicate that stress reactions to a simulated stress task can be measured by physiological methods, i.e. changes in heart rate and cortisol levels. More importantly, the data reveal that stress affects our movement quality, which can be measured by movement features calculated from motion capture data, such as smoothness and jerkiness of the movements. This study illustrates the possibility to implement passive motion capture systems as a diagnostic tool for evaluating mental (stress) and physical health through the measurement of movement quality. In future studies, we plan to apply these movement quality analysis techniques in a high school classroom during class to see if there is a difference in movement quality depending on students' stress levels.

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Disclosure statement

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Conflict of interest

The authors state no conflict of interest.

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IMPOSING DEMANDS ON PRECISION INFLUENCES THE HANDS DIFFERENTLY DURING ALTERNATED DISCRETE TOUCHING

original paper
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ABSTRACT

Purpose. How demands of precision influence the performance during alternated discrete touching is not well established in the literature. Hence, we compared both hands performance during alternated touching, manipulating the precision demand.

Methods. Overall, 23 right-handed adults participated in this study. The first task consisted of alternated touching with a pencil on both sides of a blank paper, performing as fast as possible, considering the first touch as reference for the next ones. Subsequently, touch dispersion and width were measured, and circular targets were drawn with those proportions. The second task consisted of performing as many hits as possible inside those targets. Apart from the delimitated target, increasing precision demand, the task parameters were equal.

Results. Movement time increased and the number of touches decreased from the first to the second task. However, the preferred hand displayed greater reductions in performance.

Conclusions. The perceptual constraint of adding a visual target affects motor control parameters in alternated touching, causing decrements in performance in both hands, but more evidently in the preferred right hand.

Key words: motor control, handedness, asymmetry, speed-accuracy trade-off

Introduction

The speed-accuracy trade-off paradigm has been tested in different contexts and tasks, and strong support has been found in its formulation (e.g., Elliott et al. [1] for a review) since Woodworth [2] and Fitts [3]. Higher movement speed leads to impaired accuracy, while higher accuracy leads to impaired speed. Previous studies have manipulated task parameters during alternated discrete touching, such as target distance and width, and investigated the characteristics of movement control in this task [4, 5]. However, perception may play an important role within this paradigm.

Perception has been defined as the interpretation and attribution of meaning to a given stimulus. It is a cognitive process involving various aspects of the central nervous system and higher-order thinking mediated by many cortical regions [6]. As such, some research has shown that visual perception affects motor responses [7, 8]. In the speed-accuracy paradigm, perception manipulations can involve visual layout changes and/or target illusions, in which both can alter performance or movement control parameters (such as precision and movement speed) during alternated discrete touching [8–10]. From the notion that motor behaviour emerges as a product of the interaction between the individual, the task, and the environment [11], the ecological dynamics approach could be applied to understand modifications in performance imposed by distinct perceptual manipulations. These modifications in task parameters can interfere in the movement system, leading to a change in the coordinative state of control [12], as the motor system fluctuates toward the most stable pattern of coordination given the novel task demands [13].

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Another way of manipulating perception within the speed-accuracy trade-off paradigm is the following: initially, participants are asked to perform alternated touches in a blank space; secondly, the touch dispersion is measured to create targets of the same diameter as those virtually produced in the first task. Applying this manipulation, previous investigation has already demonstrated that performance decreases regarding movement speed in the target condition, also affecting movement control by means of increasing the number of sub-movements [14]. This result suggests that, indeed, the affordances (i.e., a clue that the environment offers to the individual [12]) provided by the drawn target can interfere in motor performance. However, in Carlton's research [14], only 5 participants were tested with the preferred hand, leaving the question open as to whether this manipulation could influence (or not) the non-preferred hand.

Within this scenario, handedness is an essential factor that affects motor responses [15], as each hand can be considered as a different effector within the same individual, which interacts differently with the constraints imposed by a given motor task. For instance, Vaughan et al. [16] analysed the impact of handedness during alternated discrete touching with a stylus in 2 side-by-side targets, aiming to perform as many touches as possible while still being accurate. These authors verified that responses with the preferred right hand were faster and more accurate, occurring in shorter movement time for tasks of similar difficulty, just as Woodworth [2] had presented long ago. Performance asymmetries and differences in movement control between hemispheres, therefore, can be key-points to understand underlying mechanisms involving perception and handedness interactions.

The preferred hand has been associated with greater control of intersegmental dynamics in predictive environment, better accounting for interaction torques during multi-joint movements [17, 18]. The non-preferred hand, however, is associated with greater stabilizing capacity, especially during conditions of unpredicted perturbation [18, 19]. Hence, in alternated touching, the preferred hand has clear advantages given the dynamic constraints of the task, likely being able to better coordinate the movement parameters to perform an increased number of successful touches. In this context, the same constraint applied in a task could selectively influence the performance of each hand, given the specific interaction of task constraints and the effector [11] (i.e., right vs. left hand). These pieces of evidence suggest that hemispheric function specialization can lead to performance differences between hands in a variety of motor tasks. Considering that manipulating the demand of precision by the available visual information can affect movement parameters [8] and that each hand has specific neural asymmetries in motor control [18], our experimental approach is relevant to understand how changes in the visual stimulus of a target can impact on motor control in both the preferred and non-preferred hand.

In the present study, we aimed to analyse the effect of manipulating the demand of precision by adding the visual information of a target during the performance of alternated discrete touching with both hands. We hypothesized that: (H_1) manipulating the demand of precision, by drawing a target in the alternated touching task, would impair both hands performance; (H_2) there would be a more significant adverse effect on the performance of the preferred hand, since this hemisphere might greatly consider environmental clues (i.e., drawn target) to specify movement parameters. This research contributes to understanding how the demand of precision influences motor control during alternated discrete touching, also providing information on distinct motor control processes operating within the mediating contralateral dominant and non-dominant cerebral hemispheres.

Material and methods

Participants

A priori power analysis for the Wilcoxon signed-rank test was conducted in G*Power to determine a sufficient sample size by using an alpha of 0.05, a power of 0.80, a medium effect size (dz = 0.55), and one tail [20]. On the basis of the aforementioned assumptions, the desired sample size equalled 23.

A total of 23 right-handed participants, in accordance with the Global Lateral Preference Inventory [21], comprised a convenience sample for this study (*M* age = 28.9 years, *SD* = 13; 10 women, 13 men). Prior to data acquisition, the task parameters and conditions were explained, without providing details on the specific aims and manipulations to be performed.

Task and demand of precision manipulation

In the adapted Fitts task employed, the participants performed repeated discrete pencil (length: 16.5 cm, weight: 5.5 g) touches on each side of a paper (A-4 size). The paper was fixed in front of the participant, who sat in a height-adjustable chair. The task time (20 s) was controlled by a digital chronometer in all trials.

The participants performed the following experimental conditions: (a) no target right hand (NT-RH), (b) no target left hand (NT-LH), (c) visual target right hand (T-RH), and (d) visual target left hand (T-LH). Only the hand performing the initial trial was randomized between subjects, as no-target conditions were always performed first.

In the no-target condition, standardized instructions were to perform as many touches as possible on each side of the paper (separated by a midline). The participants were free to touch the paper with the pencil wherever they wished, with the only constraint that they should use their first touch as the reference for the next ones, during the 20-s trial. This procedure was selected for 2 reasons: (1) to assure that the performance of the alternated touching was as fast and as accurate as possible, and (2) because we intended to allow the participant to choose a preferred distance between the targets. Moreover, delimiting a specific distance would possibly create an internal constraint related to where the touches should be directed at, which could influence the demand of precision. The task was performed with both hands.

Subsequently, 2 measures were taken from the no-target condition to draw circular targets for the target condition: the smallest distance between a left and a right-side point, and the greatest distance between 2 points in the same side. These measures allowed experimenters to draw 2 circular targets that were the same distance apart from each other as the touches performed in the no-target condition, as well as targets with the same diameter as the touch dispersion performed in the no-target condition. This procedure was performed individually, producing unique target settings for each participant. With this measuring approach, the differences in performance between the no-target and the target conditions can be interpreted as solely caused by the effect of the perceived target – since the area available for touching was equal in size to the dispersion produced in the no-target condition. Then, the subjects performed the target conditions, with both hands, following the same instructions as in the previous condition (to perform hits as fast and as accurately as possible during the 20-s trial). Figure 1 illustrates the experimental procedures performed to set each target between conditions. When the participants finished the no-target condition, they were instructed to wait outside of the room while the target condition was being prepared. The subjects had a 2-minute rest between hands and conditions.

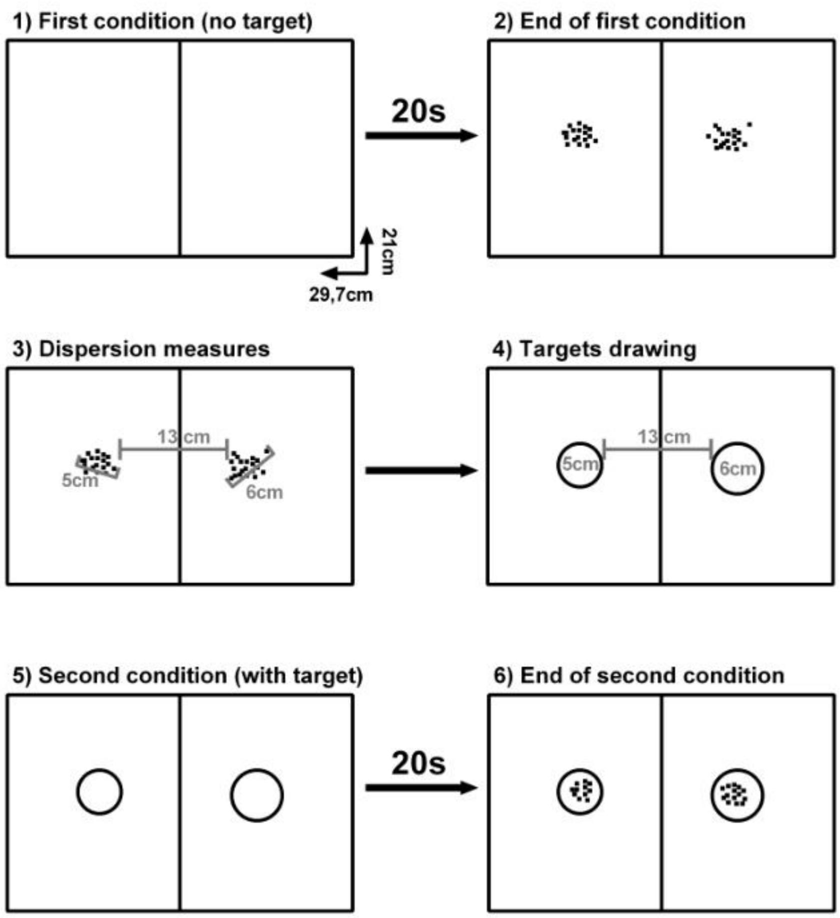


Figure 1. Experimental procedures

Hence, from one condition to the other, besides performing with both hands, the participants underwent a manipulation that increased the demand of precision, keeping all task parameters the same, except for the visual perception constraint created by the drawn target. The individuals had visual feedback on their performance throughout the entire protocol. In both conditions, instructions were given to ensure no focus on either speed or accuracy was prioritized.

Data acquisition and statistical analysis

To precisely compute the number of successful touches (ST), we recorded trials with an iPhone 6s at 60 Hz (Apple, Inc.). Two researchers viewed the videos at 1/4 the original speed, and each researcher counted the number of ST twice (all touches were considered successful in the no-target condition, while only the ones inside the target were considered successful in the target condition). No cases of divergent results in the counting happened. The participants performed the task sitting comfortably in a height-adjustable chair, in a quiet and well-illuminated room.

The distance measures presented in Figure 1 were acquired by using a rigid metric tape with a precision of 1 mm. Targets were further manually drawn with the assistance of a compass and checked by 2 researchers to assure measurement precision. We computed the following variables: the number of ST and total touches (TT), movement time (MT) $\left(\frac{20s}{TT}\right)$, target distance and width (Figure 1), and index of difficulty (ID), representing the rate of information processing in bits, in accordance with the Fitts equation: $\log_2\left(\frac{2d}{w}\right)$. Additionally, we calculated percentage performance differences $\left(\left(\frac{(Tperformance * 100)}{NT_{performance}}\right) - 100\right)$ for ST and MT between the no-target and target conditions in order to compare the effect of the increased demand of precision in each hand.

Normality and sphericity were not verified by the Shapiro-Wilk or Mauchly's tests, so we presented data as median and interquartile range. Comparisons between ST and MT in each condition were performed with Friedman's test, followed by the Wilcoxon signed-rank test when necessary. Significance correction was performed in the Wilcoxon test and set at $p < 0.025$. Considering that distance and target width were not the same between right and left hand, comparing ST and MT between hands would not be appropriate.

Aiming to understand in which hemisphere the demand of precision exerts greater influence in movement control parameters, we compared the percentage performance difference of each hand using the Wilcoxon test. IDs, target distance, and width were also compared between hands with the Wilcoxon test. Effect sizes for all the Wilcoxon tests were calculated by dividing the Z value by the square root of n (number of observations over both time points) [22] and interpreted in accordance with Cohen [23]. To check if males and females did not differ in their performance, the Mann-Whitney U test was conducted to compare their results. All data were processed in SPSS (v. 23, IBM Statistics) and, except when differently specified, the significance was set at $p < 0.05$.

Ethical approval

The research related to human use has complied with all the relevant national regulations and institutional policies, has followed the tenets of the Declaration of Helsinki, and has been approved by the authors' institutional Ethics Committee.

Informed consent

Informed consent has been obtained from all individuals included in this study.

Results

No performance differences were observed between males and females, for any of the variables analysed ($p > 0.153$; $Z < 1.42$). Table 1 presents comparisons between ST and MT in each experimental condition, as well as comparisons between IDs, target distance, and width between the right and left hand.

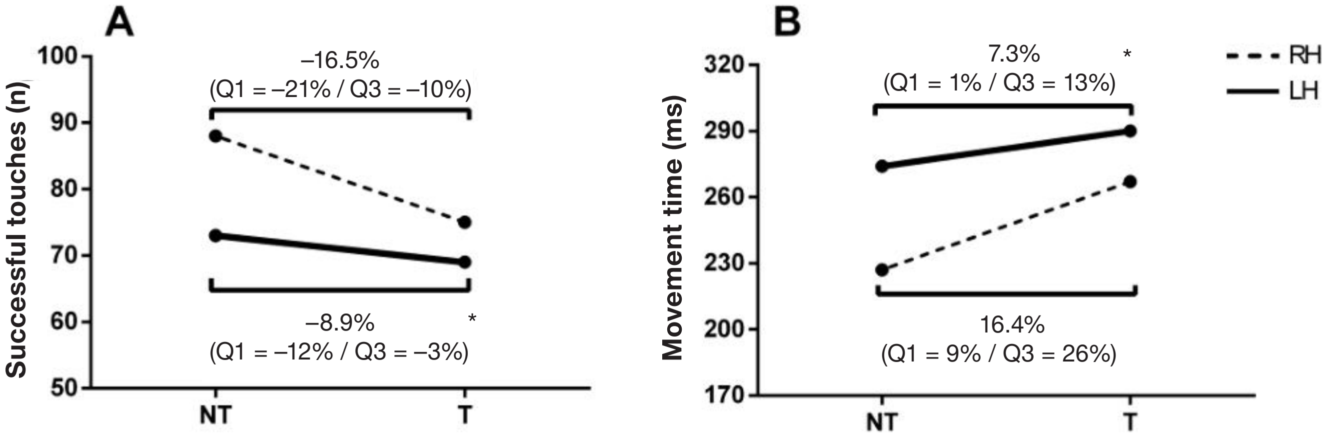
In the condition with targets, performance decreased for both hands. Effect sizes were considered large for the reductions in ST and MT of the right hand ($r = -0.60$) and moderate for the left hand ($r = -0.47$). A greater target size was verified with the non-preferred left hand, with a moderate effect size ($r = -0.46$), while the other variables did not differ significantly. The number of unsuccessful touches (out of the target area) was not significantly different between hands (right hand: 1, Q1 = 0, Q3 = 2; left hand: 1, Q1 = 0, Q3 = 2; $p = 0.55$; $Z = -0.60$). Figure 2 presents the amount of ST and average MT in both hands and conditions, as well as the performance percentage differences in ST and MT.

The percentage difference was significantly higher for the right hand in both variables, with large effect sizes ($r = -0.53$), which means that the preferred hand performance was proportionally more affected by the demand of precision compared with the non-preferred hand.

Table 1. Comparisons of successful touches, movement time, index of difficulty, distance, and target width in each experimental condition

	NT-RH	NT-LH	T-RH	T-LH	X^2	*p*
	Median (Q1–Q3)	Median (Q1–Q3)	Median (Q1–Q3)	Median (Q1–Q3)		
ST	88 (78–97)	73 (69–82)	75 (65–82)[a]	69 (59–75)[b]	52.3	< 0.01
MT (ms)	227 (206–255)	274 (244–290)	267 (231–303)[a]	290 (261–326)[b]	44.8	< 0.01
					Z	
		ID	2.20 (2.07–2.68)	2.16 (1.67–2.54)	–1.76	0.078
		Distance (cm)	6 (4.5–9.9)	7.5 (4.8–9.8)	–0.75	0.456
		Width (cm)	2.6 (2.1–3.4)	3.1 (2.4–4.1)	–3.13	0.002

NT – no target, T – with target, RH – right hand, LH – left hand, Q1 – first quartile, Q3 – third quartile, ST – successful touches, MT – movement time, ID – index of difficulty
[a] $p < 0.01$ vs. NT-RH ($Z = –4.10$), [b] $p < 0.01$ vs. NT-LH ($Z = –3.15$)
Significance in Wilcoxon comparisons was corrected to $p < 0.025$.



n – number of touches, NT – no target, T – with target, RH – right hand, LH – left hand, Q1 – first quartile, Q3 – third quartile
* $p < 0.05$ vs. RH ($Z = –3.62$)

Figure 2. Percentage difference in successful touches (A) and movement time (B) between hands in each condition

Discussion

The main result of this study was a reduction in ST and an increase in MT when a visual perception constraint was added to the task, which increased the demand of precision. The drawn target manipulation affected proportionally more the preferred hand performance. Thus, both initial hypotheses were confirmed. The findings imply that how the targets are built and perceived in alternated touching can provide different strategies to control accuracy and speed. Indeed, the trade-off between speed and accuracy is one of the most consistent paradigms in motor behaviour. Speed might be diminished at the cost of increased accuracy and vice-versa, depending on the task constraints. The following factors are known to influence performance during alternated discrete touching: time available for feedback information [2, 24], control of acceleration and deceleration movement phases [25], limited capacity of information processing in the central nervous system [3, 26], variability in the motor output [27], and parametrization of movement control [28]. In line with these previous investigations, our results advance with the speed-accuracy trade-off paradigm by verifying the influence of the demand of precision in alternated touching.

The performance losses in the target condition are consistent with previous research analysing perception effects on motor tasks [8–10]. Applying a very similar protocol, Carlton [14] revealed that MT was, on average, 22.7% slower in the condition with a delimited target, which is very similar to our observed 19.7% value (Figure 2, panel B, average value for RH). Both these results refer to the preferred hand performance, indicating a consistent finding regarding how much of movement speed can be compromised when a target is delimited with previous dots displacement. Similarly, Skewes et al. [9] manipulated perception in a discrete touching task, using same-size targets with a visual illusion that made them look different. These authors verified that bigger target perceptions led to higher amounts of ST, highlighting the impact of perception on motor control. The similarity to our experimental approach and results lies in the fact that our participants judged the target to be bigger in the first condition (without any target), leading to performance impairments when target perception suggested a smaller area to touch.

From a theoretical standpoint, the ecological dynamics approach poses that the perception-action cycle is influenced by a constant interaction between 3 factors: the individual, the environment, and the task constraints [11]. Within this perspective, performance differences between the experimental conditions were expected, as the addition of the target imposes an additional constraint on movement control. According to Carlton [14], the condition with a target requires the individual to divide their attention into both the spatial and the temporal monitoring of the task – leading to a less efficient use of visual feedback [29], which explains the performance loss. It is also worth noting that, in the current investigation, all participants used the entire virtual target area in the target condition, which provided trials with equivalent movement distance and spatial accuracy demands. Hence, it is safe to conjecture that the performance differences are primarily attributed to the increased precision demand perceived by the participant.

Regarding the preferred and non-preferred hand performances, our results also agree with prior research by Woodworth [2], Todor and Doane [30], and Vaughan et al. [16], by verifying greater precision and speed for the preferred hand on similar IDs. Although task parameters slightly varied between hands, hampering between-hand comparisons, there was a clear performance superiority with the preferred hand (more ST and faster MT). Previous research has suggested distinct control forms between the 2 hemispheres of the brain, noting linear trajectory advantages and better dynamic movement control for the preferred hand [19]. These control asymmetries relate to our findings because of the dynamic nature of the alternated touching task. Hence, the preferred right hand was expected to perform better given its increase capacity to coordinate movement parameters.

How each hand was differently impacted on by the precision manipulation performed in the present research also fits within the ecological dynamics framework. Considering that the effectors are different (right vs. left hand), the interaction with the task constraint is also modified within the perception-action cycle. As such, it seems that the drawn target can be considered as an affordance [12], with a stronger influence in the right hand, causing it to fluctuate towards a proportionally slower state of stability within the alternated touching coordinative movement pattern. Further supporting our findings, the dynamic dominance model, proposed by Sainburg [18], can also aid the interpretation of our results. According to the model, the left cerebral hemisphere is specialized in the dynamic aspects of motor control, such as intersegmental coordination and torque interactions during multi-joint movements. Hence, we speculate that the parameters specified by the increased demand of precision (drawn target) are mostly used to control movement dynamics and coordination, thus greatly affecting the preferred hemisphere performance. Contrarily, the right cerebral hemisphere, specialized in impedance control (stabilizing and positioning capacity), might not use perceptual visual clues as a major affordance related to the control pathway specifying movement parameters. Taken together, this theoretical background explains why the same manipulation could produce distinct results in each hand.

Some limitations, however, should be noted. While our behavioural data do not allow a confirmation of this explanation, this theoretical approach fits the current literature and explains the relatively higher performance loss, from one experimental condition to the other, in the preferred hand. Using a pen on a blank sheet of paper allows a condition without target only in the initial part of the task, as further dot placements create a supposed target reference. Applying this protocol in a digitalized manner, with additional kinematic measures in both right- and left-handed participants, would also provide further information on the topic.

Conclusions

Imposing demands of precision, by adding a circular target to the alternated touching task, reduces the number of ST and increases MT. Possibly, the perceptual constraint of a visual target affects motor control parameters, thus causing the decrements in performance. We also conclude that this manipulation has a superior influence on the right hand, likely owing to the left cerebral hemisphere specificity in dynamic control, which may be more prone to use environmental clues to set movement parameters. These results add to the literature of motor control, enhancing the comprehension of precision demands during alternated discrete touching.

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Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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HOW DOES THE AMOUNT OF MOVEMENT AND OBSERVER EXPERTISE SHAPE THE PERCEPTION OF MOTION AESTHETICS IN DANCE?

original paper
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ABSTRACT
Purpose. Research on empirical aesthetics suggests that specific kinematic parameters are related to the perception of motion aesthetics. Furthermore, an observer's expertise seems to be related to the perception of motion aesthetics when complex biological motion stimuli are present. The central aim of this study was to investigate whether the amount that specific body parts moved during a complex motor skill was related to the perception of motion aesthetics in observers with different levels of sensory-motor expertise.
Methods. Overall, 36 participants divided into 2 groups (18 dancers and 18 non-dancers) were asked to indicate their perceived motion aesthetics when they watched stick-figure video sequences of 3 different semi-standardized dance skills. The stick-figure video sequences were generated from original motion stimuli, and motion aesthetics were measured via Likert scales.
Results. The perception of motion aesthetics in relation to the amount that specific body parts move is skill- and expertise-specific. Dance poses are perceived similarly by dancers and non-dancers, but motion aesthetics during dance jumps and turns are perceived differently. Furthermore, the amount that specific body parts move affects whether the observer perceives the motor skills as more or less aesthetic.
Conclusions. The observer's sensory-motor expertise regarding the observed motor skills can shape their perception of motion aesthetics. The findings of this study demonstrate that there is a skill- and expertise-specific relationship between motion kinematics and motion aesthetics.
Key words: empirical aesthetics, Likert scale, markerless motion capturing, motion perception, stick-figure video sequences

Introduction

Imagine a dancer performing a complex turn during a dance; the dancer's goal is to execute the turn in an aesthetically pleasing manner. During the creative process, the dancer may implement different dance techniques, motions, and body expressions to satisfy the performance demands and attract the attention of the audience in terms of aesthetics. The resulting impression of the motor skill may differ across the audience members, especially across observers with and without sensory-motor experience related to the observed skill. The following questions arise: What shapes an individual's impression of a skill being performed in terms of aesthetics? Is it affected by the performer's motion kinematics, the observer's expertise, or the contextual interaction of both factors? With these questions in mind, the central aim of this study was to investigate whether the amount that specific body parts move during a complex motor skill is related to the perception of motion aesthetics in observers with different experience.

Previous research on (empirical) aesthetics has investigated the properties and features of aesthetic objects, the resulting response mechanisms to such objects by the observer, and the resulting interplay between the object and the observer in a given context [1–5]. When aesthetic objects associated with biological motion are studied, as is typical in artistic sports and performing arts, aspects of an embodiment are additionally taken into account [6–9]. For the purpose and understanding of this paper, the following key

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terms are defined: *Motion aesthetics* is defined as the relationship between properties and features of motion stimuli, the resulting response mechanisms to such stimuli by the observer(s), and the interplay between aspects of the motion stimuli and an observer's response to such stimuli within a given context. *Aesthetic motion perception* or *the perception of motion aesthetics* refers to the overall perception of aesthetic (biological) motion stimuli. Furthermore, the term *aesthetic features* refers to parameters that are related to stimuli's perceived motion aesthetics, which have the potential to increase stimuli's motion aesthetics.

In dance and performing arts, the object of interest can, in general, not be observed independently from the artist's body. Compared with watching nonbiological figural shapes or paintings of landscapes for example, watching human biological movement evokes different response processes by the observer [3, 6, 10]. Although the brain areas whose activity is correlated with aesthetic perception are independent of the stimulus modality [1], previous research on the so-called action observation network [11] has shown that specific brain regions, such as the mirror neuron system, as well as the premotor and occipitotemporal cortices, respond equally to the physical and observational learning of complex skills. Furthermore, it has been argued that cognitive bottom-up mechanisms, as well as relevant top-down mechanisms, are integrated during the visual perception of biological motion [10]. Consequently, to shed light on the interplay of aesthetic motion perception, the relationship between the object-driven aesthetic features of motion stimuli and an observer expertise to such motion stimuli should be investigated cohesively. In this study, contextual factors were controlled for and original motion stimuli were reduced with the use of stick-figure video sequences, thereby preventing biases related to visual perception [10].

The perception of motion aesthetics in complex motor skills seems to be expertise-specific. The findings of studies among performers with different levels of expertise are quite consistent. Motor skills presented by performers with higher expertise levels are perceived as more aesthetically pleasing than the same motor skills exhibited by performers with lower expertise levels [12, 13]. However, the relationship between the observer's sensory-motor and contextual experience and the perception of motion aesthetics seems to be complex.

Expert and novice observers of dance seem to implement different strategies when watching [14], discriminating [15], and evaluating [16] dance sequences. Novice dance observers, compared with expert dance observers, have longer fixation times and different fixation locations when watching a dance sequence [14]. The observer's expertise regarding the perceived motion stimuli may thus be related to what the observer can perceive when watching a motor skill, which then may also be related to their aesthetic motion perception (cf. *aesthetic triad*) [2]. For example, female dancers are more able to discriminate point-light displays of female dance skills than male dancers. Although dancers in general outperform both male and female non-dancers, authors suggest that female dancers outperform their male counterparts as well as female and male non-dancers because they have both visual and motor experience of the female dance skills that are discriminated [15]. Furthermore, naïve dance observers seem to aesthetically prefer the dance skills that they do not think they are able to perform [16]. Consequently, the degree of (multi)sensory experience seems to be related to an observer's ability to perceive a motor skill's motion aesthetics. Whether observers with sensory-motor experience differ in their perception of motion aesthetics compared with observers without sensory-motor experience watching the same motor skills is still open for investigation, and the answer to this question may shed light on whether motion aesthetics are more strongly related to the object, the performer, or the interaction of both factors.

Previous research on motion aesthetics has pointed out specific object-driven aesthetic features. On the one hand, qualitative and dance-specific motion descriptors, such as the direction of movement, a high (joint) flexibility of the performer, or a large and diagonal spread of the body during postures, have been identified [6, 7, 17]. On the other hand, quantitative and motion-related kinematic parameters, such as the amplitude or range of motion of specific joints, balance time, vertical angles of body segments, jump height, (turning) speed and movement velocity, as well as motion smoothness [6, 12, 18, 19], have been described. Although methodological differences within these studies impede the identification of overarching aesthetic features, the relationship between kinematic parameters and the perception of motion aesthetics has been shown to be skill-dependent. The perceptual ratings of dance skills seem specific to the requirements and mechanics of the motor skill [6, 18]. If a motor skill requires the performer to jump, kinematic parameters of jumping ability seem to be related to the aesthetic perception of the skill. In contrast, if as kill requires balance and limb displacement, the balance time and elongation angle of the moving limb may be the kinematic parameters related to the observer's aesthetic ratings [17, 18]. Therefore, the relationship between motion kinematics and motion aesthetics is quite skill-specific, and skill-independent relationships between motion kinematics and motion aesthetics are limited. It is thus assumed that comparing stick-figure video sequences of motor skills with different requirements and modifying a skill-independent kinematic parameter can provide information to fill the research gap and is a useful approach, especially to investigate the relationship between object-driven kinematic parameters, such as the amount that specific body parts move, and the perception of motion aesthetics.

In general, the human visual system allows an individual to perceive moving lines, corresponding body angles, and motions in space when they observe stick-figure video sequences [10]. Regarding angle perception and discrimination, psychophysical theories have suggested critical values for just-noticeable differences (JNDs) in visual perception (cf. *Weber's law* or *theory of line combinations*) [20]. In psychophysical research, JNDs between 1.5° and 3.5° indicate that the human visual system detects angular changes of at least approximately 3°. Those findings are hardly transferrable to the perception of complex biological motor skills, where multiple body angles and segment orientations are holistically viewed and perceived. However, research on body angle discrimination and related visual biases has suggested that there is a critical JND in the magnitude of body angles that can be perceived. Body angles above a conservative perceptual threshold of 15° per body segment seem to be applicable for complex biological motion kinematics [20–23]. For example, Giblin et al. [21] investigated whether expert coaches, novice coaches, and tennis players differred in their ability to detect kinematic changes in tennis serves. The angle of maximum knee flexion, the angle of maximum trunk rotation, and the height of ball toss were manipulated by a tennis player executing the tennis serve. Observers wrote down whether they perceived changes in point-light sequences of the manipulated tennis serves. The results indicate that coaching expertise provides no additional benefits in detecting holistic kinematic changes. However, with regard to perceived changes in knee flexion, experts seem more sensitive in their ability to detect knee flexion angle differences between –5.8° and +7.5° in a reference tennis serve [21].

Investigating whether the amount that specific body parts move affects the perceived aesthetics of dance skills requires a skill-independent comparison of the motion kinematics with the perceived motion aesthetics. Measuring the amount of movement in complex motor skills such as dance jumps, poses, and turns by calculating and comparing the summed angular motion difference per second of movement enables kinematic parameters to be compared across different skills. Furthermore, this skill-independent approach and the kinematic measure of the summed angular motion difference per second of movement may help reveal previous research investigating the relationship between motion kinematics and motion aesthetics quantitively in terms of skill-specific kinematic parameters [12, 18, 19], qualitatively [13, 24], and technically [24].

In sum, previous research has suggested that there are specific kinematic parameters related to the perception of motion aesthetics. However, the formerly assessed kinematic parameters seem to be strongly skill-specific, and skill-independent parameters and their relation to motion aesthetics still need to be investigated. Furthermore, an observer's expertise seems to be related to the perception of motion aesthetics and should be taken into account when one aims to identify fundamental kinematic parameters of motion aesthetics. According to previous research, observers' holistic impression when aesthetically perceiving complex motor skills has not yet been studied quantitively or skill-independently [17, 18, 25]. Additionally, observers with different expertise may implement different perceptual strategies when observing motion stimuli, which then shape their motion aesthetics differently [13, 14]. Consequently, measuring kinematic variations of complex motor skills in combination with subjective indications of motion aesthetics from observers with different sensory-motor expertise to such motor skills seems to be an appropriate approach to obtain insight into the relation between motion kinematics and motion aesthetics. Thus, it seems to be the method in which observers can indicate their perceived motion aesthetics in the most unbiased manner possible [3]. Furthermore, implementing rating scales, such as Likert scales, is appropriate when large numbers of displays have to be rated aesthetically [26].

In this study, it was hypothesized that the amount that specific body parts move during a complex motor skill would be related to the perception of motion aesthetics by observers with different experience. More precisely, it was hypothesized that the amount that specific body parts move and its relation to the perception of motion aesthetics would differ depending on the dance skill being performed. Second, it was hypothesized that the perception of motion aesthetics by observers with and without sensory-motor experience would differ depending on the amount that specific body parts move. Moreover, how the amount that specific body parts move shapes the perception of dance skills regarding the extent to which they are considered aesthetically was explored.

Material and methods

Participants

The study sample consisted of 36 participants in 2 groups: n_1 = 18 participants with dance experience in classical, modern, and jazz dance (dancers) and n_2 = 18 participants without dance experience (non-dancers). The dancers (16 females, 2 males) were 29 ± 11 years old and had an average of 16 ± 12 years of dancing experience with 6 ± 5 training hours per week. The non-dancers (9 females, 9 males) were 22 ± 2 years old and reported not having any dance experience but participated in different sports regularly with an average of 6 ± 5 years of general sport experience and 3 ± 2 hours of practice per week. The subjects' task was to indicate their perceived motion aesthetics when they watched stick-figure video sequences of 3 different semi-standardized dance skills, namely, jumps, poses, and turns.

An additional stimulus group of 9 experienced female dancers (mean age: 29 ± 3 years) was recruited to generate the video stimuli. The dancers reported having substantial experience in different dance styles, such as classical dance, modern dance, and jazz dance. Their average duration of dancing experience was 21 ± 8 years, with 4 ± 1 hours per week of regular practice. The dancers' task was to perform semi-standardized jumps, poses, and turns.

The study participation was voluntary. All participants received an hourly credit if administrable for their studies.

Instruments

Stimuli generation

The procedure used to generate stimuli was similar to the one proposed by Vinken and Heinen [17]. For the sake of clarity, the relevant steps are described here.

The dancers who visited the gymnasium were informed about the general purpose of the study, as well as the video stimuli generation process. Each dancer filled out a short questionnaire about their dance experience. The dancers were asked to individually warm up and prepare for the upcoming task. Video stimuli for the 3 dance skills, namely, jumps, poses, and turns, were generated randomly for each dancer.

Each dancer was informed about the motion prerequisites of the dance skill being performed first, for example, the jump. The instructions and prerequisites of the 3 dance skills were as follows. For the dance jump, the dancer was told: 'Stand upright with your feet hip-width apart and your arms hanging loosely. Jump from the left leg with a 45° turn to land on the right leg and then come back to the upright stance with your feet hip-width apart and arms positioned to the side of the body. Please show variations of this jump by individually varying the movement of the legs, arms, trunk, and whole body as well as accentuation and complexity'. For the dance pose, the dancer was told: 'Stand upright with your feet hip-width apart and arms hanging loosely. Use the left leg as the standing leg, exhibit a one-legged pose and then come back to the upright stance with your feet hip-width apart and arms positioned to the side of the body. Please show variations of this pose by individually varying the movement of the legs, arms, trunk, and whole body as well as accentuation and complexity'. For the dance turn, the dancer was told: 'Stand upright with your feet hip-width apart and arms hanging loosely. Do a 450° turn to the left with your right leg as the standing leg and then come back to the upright stance with your feet hip-width apart and arms positioned to the side of the body'.

The dancer was allowed to individually practise the skill and ask questions about the movement variations, instructions, and the video stimuli generation process. Then, each dancer was asked to perform at least 4 variations of the first dance skill. Afterward, each dancer was asked whether they were satisfied with their performance or wanted to do another repetition or variation. When at least 4 variations of the first dance skill were successfully performed and captured, the dance skill performance and video capture processes were repeated twice for the remaining dance skills. When each dancer performed at least 4 variations of each dance skill, she was debriefed.

The dance skills were performed in a capture area of 5 × 5 meters, and they were videotaped by 6 video cameras sampling at 60 Hz (640 × 480 pixels). Each recorded video sequence was processed with a silhouette-based computer-based algorithm to extract the movement kinematics (iPi Motion Capture™, iPi Soft, Russia). The video recordings from all 6 cameras were used to generate a 3D volume model of a human body consisting of a head, a trunk, 2 upper and lower limbs, 2 hands, 2 thighs and shanks, 2 feet, and the appropriate joints, namely, the neck, shoulders, elbows and wrists, chest, hips, knees, and ankles.

Stick-figure video sequences were generated from the extracted movement kinematics. To that end, the original video recordings were reduced to the kinematic motion information, which allowed potential contextual and bodily biases to be controlled [10]. To achieve a sufficient variety of stimuli dance skills, uniform variations of dance skills were grouped, and one stick-figure sequence was randomly selected for the stimuli sample. The uniform variations consisted, for example, of equal implementation of arm and leg displacement, head and trunk involvement, and dance skill-specific movement vocabulary. Ten stick-figure video sequences of each dance skill were selected for stimuli presentation and evaluation, thus representing a sufficient variety of different jumps, poses, and turns. At the end of the steps mentioned above, there were 30 stick-figure video sequences of dance skills: 10 for jumps, 10 for poses, and 10 for turns.

Stimuli evaluation

The stick-figure video sequences of the dance skills were prepared for a randomized stimuli presentation. Each video sequence of the first dance skill, for example, the pose, was presented twice at the original tempo on a 2.5 × 1.8-meter projection screen. The dancers and the non-dancers were asked to respond to the question: 'How do you perceive the sequence aesthetically?' [16, 27] by selecting the corresponding number on a 7-point Likert scale ranging from –3 to +3 [28] on a piece of paper. When the first dance skill was evaluated, the same procedure was repeated for the remaining 2 dance skills. This procedure took approximately 30 minutes per participant. Neither the terms 'aesthetics' nor 'aesthetically' were defined so that the participants answered the question in the least unbiased manner possible [3]. Ten responses were recorded per participant and dance skill, which resulted in a total of 1080 values that were used for data analysis.

After the participants' responses, the dance skills were divided into 2 groups, the 5 most and 5 least aesthetically perceived ones. Therefore, the median splits of the participants' responses to the dance skills were assessed for each dance skill [28].

Procedure

The dance skills were evaluated in 3 phases. First, each dancer and non-dancer was invited separately to a laboratory room at the local university. They were informed about the general purpose of this study, signed an informed consent form, and completed a short questionnaire about their dance experience. Afterward and before the data were collected, the experimenter introduced the evaluation procedure by showing exemplary stick-figure video sequences and explaining the data collection process. Likert scale assessments were performed separately for each of the 3 dance skills, and the jumps, poses, and turns were presented in a random order for the participants.

Second, to collect the study data, 10 stick-figure video sequences of the first dance skill, for example, the turn, were randomly presented to each participant at the original tempo. Each stick-figure video sequence was presented twice in the middle of the screen. After each turn, the participant responded to the question: 'How do you perceive the sequence aesthetically?,' which was written on the presentation slide. The responses were recorded on a piece of paper with a 7-point Likert scale. After the participant responded, the stick-figure sequence for the next turn was presented. This procedure was repeated for each of the 10 turns. After evaluating the first dance skill, the participants were allowed to take a short break. The same procedure was repeated twice for the remaining dance skills. The participants were not pressured to respond quickly, but they were instructed to indicate the first response that came to mind.

Third, after data collection, each participant was debriefed and received an hourly credit if administrable for their studies.

Data analysis

Data analysis was conducted with the statistical software R (R Core Team, 2018). The data set of one trial contained angle-time information for 63 variables that were divided into 3 categories: (1) whole-body translation was defined by 3 variables (x-, y-, and z-position of body); (2) whole-body rotation was defined by another 3 variables (x-, y-, and z-rotation of body); (3) the joint movements of each of the 19 joints were defined by 3 variables (x-, y-, and z-rotation of each joint). The trials lasted an average of 4.39 seconds with a standard deviation of ± 0.57 seconds. First, each trial's variables were time-normalized by spline interpolation to ensure structural comparability between trials of different durations [29]. Second, the time-normalized trials of each dance skill in each of the 2 categories (more vs. less aesthetic) were averaged (see *Stimuli evaluation*). This approach resulted in one time-normalized data frame representing an 'average' performance of a 'more aesthetic' skill and one time-normalized data frame representing an 'average' performance of a 'less aesthetic' skill. This was done for each of the 3 skills. Third, the summed angular motion differences of the variables corresponding to each body segment (1. movements of the left arm, 2. movements of the right arm, 3. movements of the left leg, 4. movements of the right leg, and 5. movements of the trunk and head) were calculated for each of the 3 skills to assess the similarity between more and less aesthetic performances [30].

The summed angular motion differences of the body segments were normalized to skill duration so that between-trial comparisons could be performed. This calculation allowed the extent to which each variable category contributed to the overall impression of motion aesthetics to be estimated. A positive difference in one variable category thus indicates that this category shows a larger amount of movement for more aesthetic skills. In contrast, a negative difference implies that this category shows a larger amount of movement for less aesthetic skills. A summed difference of zero denoted that both the more and less aesthetic skills exhibited the same amount of movement in the particular categories. For example, a movement of 90° in the elbow joint in one second of movement and another movement of 45° in the elbow joint within the same second were represented as a summed angular motion difference of 45°. This procedure was performed to compare the dancers' and non-dancers' indications of perceived motion aesthetics by the level of the observer's expertise.

Finally, a conservative critical value of 15° was chosen to differentiate between a perceptually relevant amount of movement, assuming that perceptual salience was larger for the larger summed angular motion differences [20–23].

Ethical approval

The research related to human use has complied with all the relevant national regulations and institutional policies, has followed the tenets of the Declaration of Helsinki, and has been approved by the authors' institutional ethics committee.

Informed consent

Informed consent has been obtained from all individuals included in this study.

Results

In accordance with the median split procedure for the more vs. less aesthetic dance skills, a descriptive inspection of the means showed a clear distinction in the Likert scale ratings of more and less aesthetic dance skills among the 3 dance skills and the 2 observer groups (dancers and non-dancers). For the dancers, the rating was 1.21 ± 0.35 vs. –0.20 ± 0.78, $t(8) = 3.71$, $p < 0.05$ for the jumps, 1.15 ± 0.63 vs. –0.39 ± 0.58, $t(8) = 4.54$, $p < 0.05$ for the poses, and 1.08 ± 0.34 vs. –0.62 ± 0.82, $t(8) = 4.10$, $p < 0.05$ for the turns. For the non-dancers, it was 1.64 ± 0.63 vs. –0.40 ± 1.03, $t(8) = 4.03$, $p < 0.05$ for the jumps, 1.33 ± 0.71 vs. –0.29 ± 0.42, $t(8) = 4.51$, $p < 0.05$ for the poses, and 1.59 ± 0.50 vs. –0.34 ± 0.81, $t(8) = 4.70$, $p < 0.05$ for the turns. On average, the rating scales of more vs. less aesthetic dance skills differed by 1.7 points, equalling 24% of the overall scale and a range of 1.41–2.04.

Figure 1 shows the dancers' and non-dancers' perceived motion aesthetics of the dance skills and their summed angular motion differences (means and 95% confidence intervals). A summed angular motion difference of ± 15° represents a conservative critical value [20–23]. Values above +15° correspond to the dance skills showing a larger amount of movement in the corresponding body part which is perceived as more aesthetic. Values below –15° correspond to the dance skills showing a larger amount of movement in the corresponding body part which is perceived as less aesthetic.

Both dancers and non-dancers perceived poses with a larger amount of movement in the right arm and the left standing leg as less aesthetic. Dancers' and non-dancers' perceptions of motion aesthetics differed for jumps and turns. Concerning dance jumps, dancers perceived dance jumps with a larger amount of movement in the left arm as more aesthetic and dance jumps with a larger amount of movement in the trunk and head as less aesthetic. Non-dancers perceived dance jumps with a larger amount of movement in the left take-off leg as less aesthetic. Concerning turns, dancers perceived turns with a larger amount of movement in the left gesture leg as more aesthetic, while non-dancers perceived turns with a larger amount of movement in the left arm as more aesthetic.

Discussion

The central aim of this study was to investigate whether the amount that specific body parts move dur-

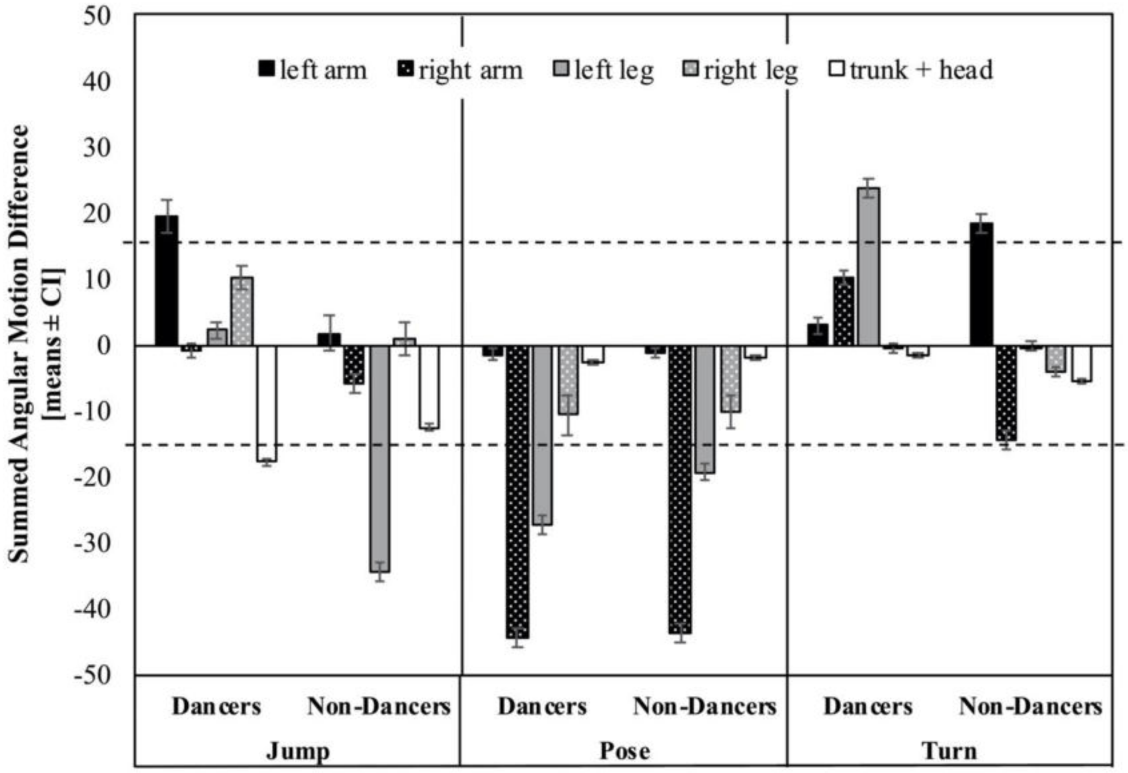

Figure 1. Illustration of the dancers' and non-dancers' perception of motion aesthetics of the dance skills in relation to the summed angular motion differences in the corresponding body parts (means and 95% confidence intervals [CI]). The dashed lines indicate a conservative critical value. Values above +15° correspond to the dance skills showing larger summed angular motion differences in the corresponding body part which are perceived as more aesthetic. Values below –15° correspond to the dance skills showing larger summed angular motion differences in the corresponding body part which are perceived as less aesthetic. The summed angular motion differences are normalized to skill duration, thus representing the amount of movement in the corresponding body part per second of movement

ing a complex motor skill was related to the perception of motion aesthetics by observers with different experience. It was hypothesized that the amount that specific body parts moved and its relation to the perception of motion aesthetics would differ depending on the dance skill and the observer's sensory-motor expertise. Additionally, it was explored how the amount that specific body parts moved shaped the perception of dance skills, which are perceived as more or less aesthetic. The results indicate that the perception of motion aesthetics in relation to the amount that specific body parts move is skill- and expertise-specific. For dance poses, the amount that specific body parts move affects dancers' and non-dancers' perception of motion aesthetics similarly, whereas dancers' and non-dancers' perceptions of motion aesthetics differ for dance jumps and turns.

Interestingly, for dance poses, a larger amount of movement in the right arm and the left standing leg was perceived as less aesthetic by both dancers and non-dancers. This finding may indicate that, concerning dance poses, less is more. Observers with and without sensory-motor experience related to the observed stimuli may perceive several accentuations within the motor skill as less aesthetic than a single accentuation [17]. Furthermore, this finding implies that simple dance skills are perceived as more aesthetic when they are executed softly and expansively [25]. However, in this case, simplicity is not related to the difficulty of the executed motor skill but rather the overall amount that the body segments move. In general, dance poses may demonstrate the performer's ability to remain balanced while reducing the magnitude of movement of specific body parts. Therefore, observers seem to prefer motor skills that may focus, for example, on a single but large inclination of the gesture leg compared with several accentuations where the gesture leg is, for example, moved up, then down, and additionally rotated at the hip and knee joint.

In dance jumps, dancers' and non-dancers' perceptions of motion aesthetics differed concerning the amount that specific body parts moved. Dancers perceived a larger amount of movement in the left arm as more aesthetic and a larger amount of movement in the head and trunk as less aesthetic. In contrast, non-dancers perceived a larger amount of movement in the left take-off leg as less aesthetic. A larger amount of movement in the head and trunk may be related to the performer's inability to stabilize the head and trunk while implementing arms and legs to perform the dance jump. To master a jump skill, the performer must be able to take off from the floor, remain a sufficient flight phase, and then prepare an appropriate landing. In general, a performer's aim during jumping is to achieve the impression of ease [6]. A lack of strength and motor control for explosive jumping can be partly compensated by using a countermovement in the trunk during take-off and landing [28]. This aspect may be 'detectable' or not depending on the observers' sensory-motor and contextual experience related to the observed skill and thus may be related to their perception of motion aesthetics.

Previous research has indicated that motor skills involving energetic jumping are perceived as more aesthetic than motor skills lacking significant horizontal or vertical displacement of the performer in space [6]. Moreover, the extent to which limbs move during jumping seems to be related to the observer's aesthetic perception of a jump. When specific body parts, namely, the left arm, move by a larger amount, dancers with sensory-motor experience related to the observed skill may perceive the movement to be more aesthetic. However, when different body parts, namely, the left take-off leg, move by a larger amount, observers without sensory-motor experience related to the observed skill may perceive the movement to be less aesthetic. Therefore, the level of accentuation and implementation of the moving limbs during jumping, as well as the observer's expertise level, can affect the perception of motion aesthetics in general.

Regarding turns in dance, the dancers' and non-dancers' perceptions of motion aesthetics differed in relation to the amount that the left gesture leg and the left arm moved. Dancers perceived dance turns in which the left gesture leg moved more as more aesthetic. Non-dancers perceived dance turns in which the left arm moved more as more aesthetic. In general, moving the limbs away from the performer's longitudinal axis increases the performer's moment of inertia, which challenges physical laws [29] and thus the performer's ability to successfully master turning. Hence, this study results suggest that motor skills which seem more difficult and challenging to perform are perceived as more aesthetic [16].

Dancers and non-dancers perceive motion aesthetics differently depending on the amount that different body parts move, which may indicate that observers with and without sensory-motor expertise may implement different strategies when perceiving and evaluating motion aesthetics. As eye-tracking studies suggest, expert and novice dance observers fixate on different body parts when watching a dance performance [14]. Therefore, the amount that different body parts move may be related to dancers' and non-dancers' perception of motion aesthetics. However, according to the results of this study, non-dancers perceive dance turns in which the left or the right arm moves a large amount differently in relation to motion aesthetics. Non-dancers perceive dance turns with a large amount of movement in the right arm as less aesthetic, while dance turns with a large amount of movement in the left arm are perceived as more aesthetic. This finding may be related to the aesthetic fundamental of symmetry [1, 26]. The dance turn performed in this study used the right leg as the standing leg. One may argue that non-dancers seek symmetry in the limbs of the same body side. While the right standing leg shows a restricted amount of movement, non-dancers may perceive asymmetry when the corresponding right arm shows a large amount of movement, an aspect that may shape motion aesthetics in such a way that the corresponding dance turns are perceived as less aesthetic.

The findings of this study reveal a relationship between motion kinematics and motion aesthetics. The summed angular motion difference and amount that specific body parts move are parameters that allow the results to be interpreted independently of the skill. It is assumed that in the perception of complex motor skills, motion aesthetics and motion kinematics are related and that, specifically, motion kinematics affect motion aesthetics [13, 19]. Different skills can be compared via a single kinematic parameter. This finding expands upon previous knowledge on the relationship of skill-specific parameters and their relations to the perception of motion aesthetics. Finally, the expertise-specific relationship between motion kinematics and motion aesthetics builds upon previous research among observers with [12, 17] or without [6, 12, 16, 19] sensory-motor experience. Therefore, future studies should replicate these methods across different groups of observers. It seems that the relationship between motion kinematics and motion aesthetics is expertise-specific [13–15] and embodied [7–9].

When interpreting the results of this study, the following limitations should be taken into account. First, the summed angular motion difference, representing the amount that specific body parts moved, was considered a kinematic parameter. It remains unclear whether focusing on a single joint instead of specific body parts can deepen our understanding of underlying motion kinematics. However, concentrating on the amount that specific body parts move by summing the kinematics of several body segments seems to provide a holistic assessment of movements compared with, for example, the inspection of single body joints and the amount that they move. Second, behavioural measures were implemented when observers were asked to indicate their perception of motion aesthetics after observing stick-figure video sequences of original dance skills. Future studies should additionally incorporate other measures, such as neurological or eye-tracking measures, to determine whether observers with different sensory-motor experience implement different strategies when assessing the motion aesthetics of complex motor skills. Third, the original motion stimuli were reduced to stick-figure video sequences. Future studies that manipulate a standardized motor skill by, for example, artificially manipulating the kinematic parameters, may deepen our understanding of the relationship between motion kinematics and motion aesthetics.

From the results of this study, the following practical implications can be derived. When aiming to create and perform aesthetic motor skills, the sensory-motor and contextual expertise of the observer and target audience should be taken into account. Depending on the observed skill, observers with sensory-motor experience perceive dance skills in which specific body parts move more as more or less aesthetically pleasing than observers without sensory-motor expertise. Furthermore, the amount that specific body parts move and its relation to the perception of motion aesthetics are skill-specific. While dancers and non-dancers similarly perceive dance poses in which the right arm and left standing leg move a large amount as less aesthetic, dancers' and non-dancers' perceptions of motion aesthetics differ for dance jumps and turns. For example, dance turns with a large amount of movement in the left gesture leg are perceived as more aesthetic by dancers, whereas non-dancers perceive dance turns with a large amount of movement in the left arm as more aesthetic.

Finally, performers, coaches, choreographers, and researchers should keep in mind that the amount that specific body parts move when a motor skill is being performed may shape the perception of motion aesthetics, especially among observers with different sensory-motor expertise related to the observed motor skill. Therefore, ways of optimizing dance motions to make them able to trigger the observer's aesthetic perception should be developed [7]. As a result, fruitful interdisciplinary collaboration between researchers and dancers may develop for the study of motion aesthetics.

Conclusions

The perception of motion aesthetics arises from a complex interplay between aspects of the object, the observer, and the context. The findings of this study demonstrate that there is a skill- and expertise-specific relationship between motion kinematics and motion aesthetics. It is concluded that an observer's sensory-motor and contextual expertise related to the observed motor skills can shape the perception of motion aesthetics. In other words, the amount that specific body parts move is related to an observer's perception of motion aesthetics. However, observers with different levels of expertise partly perceive different motion kinematics as more or less aesthetically pleasing. Although original motion stimuli were reduced to stick-figure video sequences of dance skills, it is assumed that this study results are generalizable to original video sequences, laboratory performances, and original performances. Fruitful collaboration between researchers and dancers regarding the study of motion aesthetics may develop in the future, broadening our knowledge on the relationship between motion kinematics and motion aesthetics. When researchers understand the underlying processes of motion aesthetics, practitioners will be able to develop and justify their (implicit) knowledge of creating and performing aesthetic motion stimuli.

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Conflict of interest

The authors state no conflict of interest.

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BALANCE CONTROL IN ARTISTIC GYMNASTS AND ITS COMPARISON UNDER THREE TRAINING METHODS: A PILOT TRIAL

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ABSTRACT
Purpose. Balance is a highly demanded motor ability in artistic gymnasts; however, it is unknown what type of training can improve this variable. The purpose was to determine if Star Excursion Balance Test (SEBT) and neuromuscular (NM) trainings are more effective than conventional artistic gymnastics training (CONV) for improving balance control in female artistic gymnasts.
Methods. Overall, 33 female artistic gymnasts were selected and randomly assigned to 3 training groups: CONV, SEBT, or NM. The Y-Balance Test evaluated balance control. ANOVA (group × time) with repeated measures was used to compare the effects of training.
Results. In the dominant lower limb, significant pre- and post-intervention differences were observed for SEBT training in the posteromedial direction (p = 0.0003; % change = 13.4), as well as in NM in the anterior (p = 0.0001; % change = 23.9), posteromedial (p = 0.0001; % change = 23.1), and total index (p = 0.0001; % change = 17.8) of the Y-Balance Test. Moreover, NM training presented significant differences compared with CONV (p = 0.0001; % change = 14.0) and SEBT (p = 0.0001; % change = 12.8) in the posteromedial direction; it also exhibited differences compared with CONV (p = 0.0392; % change = 8.8) and SEBT (p = 0.0065; % change = 11.3) in the total index.
Conclusions. NM training results in a significant improvement in balance control compared with CONV and SEBT training in female artistic gymnasts.
Key words: proprioceptive training, neuromuscular training, sport, athletes

Introduction

Artistic gymnastics is a sport characterized by high-flying acrobatics and feats of strength [1]. However, it also requires other motor capacities such as flexibility, agility, and balance in the upper and lower limbs while performing motor skills (jumps, landing, push, and pull) in extreme joint positions [2]. Artistic gymnastics consists of 4 apparatuses for women (jump, uneven bars, balance beam, and floor exercises) [3]. The prevalence of injuries in artistic gymnastics is especially worrying, as younger athletes are being recruited, and they are in very early stages of motor and musculoskeletal development [4]. Specifically, in collegiate artistic gymnastics, an injury rate of 9.2–22.7 injuries per 1000 hours of exposure is reported, and about 70% of these injuries occur during disassembly from the apparatus [5]. Taking this information into account is important to understand the factors that could influence injuries and, subsequently, decreased sports performance.

The International Gymnastics Federation determines that the most difficult apparatus for women's gymnastics is the balance beam [3]. This apparatus is one of the most demanding disciplines in general female competition and requires the ability to balance to a high level, as it has an extremely small (10 cm) surface support with a height of 1.25 m and a length of 5 m. In this context, a joint injury impairs the proprioceptive system, causing the musculoskeletal system

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to be more prone to repetitive injuries and decreased motor abilities, especially balance control during the performance of complex acrobatic elements [6].

The difficulty of the apparatus forces artistic gymnasts to demonstrate the ability to control balance during performance. The balance control represents the subject's ability to maintain the centre of mass within a support base and is considered a fundamental motor capacity for the execution of activities of daily living and sports [6–8]. Balance control requires constant postural adjustments owing to the displacement of the centre of mass, all of this through sensory and neuromuscular mechanisms that try to keep the centre of mass within the support base [6, 7, 9]. The balance control deficit mainly affects people with various pathologies, but less likely gymnasts as they usually have an adequate development of balance control since the centre of their trainings consists of exercises on balance beam. Therefore, determining a possible training focused on improving balance control in artistic gymnasts could be beneficial for optimizing athletic performance [5, 7].

Artistic gymnastics commonly bases its training on the development of flexibility, power, balance, lumbar-pelvic strengthening (core), and strengthening of the upper and lower limbs [10]. In recent years, various sports have used training based on proprioception and neuromuscular responses to improve balance control. These interventions are training through the Star Excursion Balance Test (SEBT) [11] and neuromuscular (NM) training [12, 13]. SEBT has been tested as a balance control evaluation method that involves loading one foot on the ground and trying the maximum reach with the opposite foot [11, 14], which challenges postural control, strength, range of motion, and proprioception of the subjects. This type of evaluation, and its use as training, is very similar to the technical performance that a gymnast must demonstrate within a competition. In turn, NM training is defined as a multi-component program [13] that integrates the development of motor skills (jumps, landings, running, etc.) with motor abilities (strength, endurance, flexibility, and balance) through plyometric and weight-bearing exercises [15–17]. Both methods – SEBT and NM training – attempt to improve balance control in various disciplines, but their effects on balance control in artistic gymnasts are unknown.

To our knowledge, there are few reports about balance control in artistic gymnasts evaluated through clinical or field tests. For this reason, the Y-Balance Test can be a tool applicable to artistic gymnasts, since it offers a simple, short-term, low-cost, and highly reliable evaluation [18, 19] and would also allow determining the effect of various trainings on balance control. In this context, the objective of this research was to establish if SEBT and NM training are more effective than conventional artistic gymnastics training (CONV) for improving balance control in female artistic gymnasts.

Material and methods

Participants

The study was a single-blind randomized controlled trial and followed the Consolidated Standards of Reporting Trials (CONSORT) recommendations. The research considered female participants aged 11–17 years belonging to the Escuela Chilena de Gimnasia (La Serena, Región de Coquimbo, Chile) (Table 1). The par-

Table 1. Baseline characteristics of the participants

Characteristics	CONV (*n* = 11) (mean ± *SD*)	SEBT (*n* = 11) (mean ± *SD*)	NM (*n* =11) (mean ± *SD*)	*p*	*F*
Age category 11–12 years (*n*)	3	2	3		
Age category 13–15 years (*n*)	6	8	7		
Age category 16–17 years (*n*)	2	1	1		
Average training experience (years)	3.1 ± 0.7	2.8 ± 0.8	2.9 ± 1.8	0.7580	0.2796
Average weekly training duration (h)	15.6 ± 2.1	15.2 ± 3.0	15.2 ± 3.4	0.9455	0.5618
Age (years)	13.0 ± 1.5	13.1 ± 1.2	13.7 ± 1.6	0.5532	0.6039
Weight (kg)	50.3 ± 8.4	51.0 ± 9.0	50.3 ± 6.8	0.9713	0.0291
Height (m)	1.54 ± 0.05	1.58 ± 0.05	1.56 ± 0.05	0.2680	1.3760
Body mass index (kg/m^2)	20.8 ± 2.7	20.1 ± 2.5	20.5 ± 2.2	0.8191	0.2009
Dominant lower limb length (cm)	82.6 ± 5.5	84.4 ± 3.6	83.8 ± 3.4	0.6256	0.4765
Non-dominant lower limb length (cm)	82.6 ± 5.6	84.0 ± 3.8	83.6 ± 3.1	0.7239	0.3326

CONV – conventional training, SEBT – Star Excursion Balance Test training, NM – neuromuscular training ticipants were selected through simple random sampling and subsequently assigned to 3 groups: CONV, SEBT, or NM training. The following inclusion criteria were considered: (a) being an artistic gymnast aged 11–17 years, (b) presenting a federated gymnast registry, and (c) having participated in a regional or national competition during the previous year. The artistic gymnasts were classified as sub-elite since they all participated in official international championships, namely South American or Pan American, and/or in national championships and obtained a classification between the 1st and 10th place of the general individual classification of their competitive category. For this research, the following exclusion criteria were applied: (a) consecutive training time less than 1 year, (b) 1 or no weekly training sessions, and (c) a lower limb injury within the previous 12 months or during the training period.

Although there is no research comparing the proposed training methods, previous reports show that a 15% change for a direction of the Y-Balance Test demonstrates significant differences between artistic gymnasts of a low and high level of specialization [20]. For this reason, accepting an alpha risk of 0.05 and a beta risk of 0.2 in a bilateral contrast, 11 participants in each training group were required to detect a minimum difference of 15% between 2 groups, assuming a standard deviation of 10% and a loss to follow-up rate of 15%.

Y-Balance Test

Balance control was evaluated with the Y-Balance Test Kit™ (Functional Movement Systems, Inc., Chatham, VA, USA) before and after the intervention. This device comprises a support platform to which 3 tubes are attached in the directions of anterior, posteromedial, and posterolateral reach. Each tube has markings in 5-mm increments. The first toe was positioned at the junction of the Y. Then, with the opposite foot, the participant had to push an ‘indicator’ along the tube trying to reach the greatest possible distance without putting the foot on the ground. The subjects were allowed to practise the test only twice in order to reduce the learning factor. At the end of the practice time, they were given a 2-minute break, and the dominant lower limb was evaluated in 3 directions (anterior, posterolateral, and posteromedial) [11, 18, 19]. In each direction, the procedure was repeated 3 times, and the average was recorded. Then, the participants rested for 5 minutes and repeated the procedure with the non-dominant lower limb. A trial was classified as invalid if the subject removed the hands from the hips, did not return to the starting position, did move the support foot (dominant), or loaded with the reach foot (non-dominant) [15, 21]. This abbreviated test is used in view of the limitations regarding the amount of time devoted to develop all directions of SEBT [18] and has demonstrated reliability and validity in predicting lower extremity injuries [19, 22].

The raw results of the Y-Balance Test were normalized. For this, the protocol described by Gribble et al. [23], who divided the distance reached by the length of the lower limb and then multiplied by 100, was used. The length of the leg was measured from the anterior superior iliac spine to the most distal part of the medial malleolus. Additionally, a total index of the Y-Balance Test was calculated by dividing the sum of the 3 directions by 3 times the length of the evaluated lower limb and then multiplying by 100 [21]. Once the Y-Balance Test was carried out, the training period of the 3 groups began. At the end of the 8 weeks of training, a post-intervention Y-Balance Test was performed in each participant.

Interventions

The intervention time was 8 weeks, with 2 weekly training sessions [21]. Each training session lasted 20 minutes, and then the usual training was continued.

Conventional training

This training consisted of 8 minutes of jogging with joint mobility and 10–12 exercises of displacements in quadruped positions, rebounds on feet, and throws of legs in all directions, with 3 series of 12 repetitions per exercise. Twelve minutes were spent practising more specific gymnastic positions, such as split, straddle, lunge, bridge, and handstand, with 3 series of 15 repetitions.

Training with Star Excursion Balance Test

This training consisted of performing a warm-up of 6–8 minutes that included joint mobility and familiarizing each limb in the 8 directions of SEBT, intercepted at 45° from one another. Then, the gymnasts executed SEBT, conducting 3 sets of 15 repetitions per direction (anterior, anterolateral, lateral, posterolateral, posterior, posteromedial, medial, and anteromedial) and lower limb, trying to reach the greatest distance with the leg without support in each of the directions, maintaining the posture for a second and then returning to the centre [11, 18, 19].

Neuromuscular training

This training consisted of quadruped positions, coordination of body segments, muscular strengthening, and bipedal and unipedal positions on stable and unstable bases, which involved weight bearing or control of the lower limbs and trunk [13, 15–17]. The NM training was based on 8 different exercises per session applied to the lower limbs, with 3 series of 15 repetitions in the unipedal exercises and 3 series of 15–30 repetitions in the bipedal exercises, depending on their complexity. The workouts were distributed as follows:

– Weeks 1 and 2: coordination exercises on a stable surface, strengthening of the lower limb, bipedal and unipedal supports, with open eyes.

– Weeks 3 and 4: coordination exercises on a gymnastic mat, strengthening of the lower limb, supports and bipedal and unipedal jumps, with the eyes closed.

– Weeks 5 and 6: specific exercises for the lower limb with TheraBand, unipedal and bipedal exercises with open and closed eyes.

– Weeks 7 and 8: use of unstable surfaces (BOSU), supports and jumps, bipedal and unipedal exercises, with open and closed eyes.

When the artistic gymnasts finished one of the previous training sessions, they proceeded to continue their traditional training on the apparatus, with the exercises difficulty adjusted to the level of each gymnast. Two different apparatuses were trained daily, with the allocation of 30 minutes to each one (jump, asymmetric parallels, balance beam, and floor) defined weekly by the coach, and ending flexibility exercises performed for 15 minutes.

Data analysis

For all analyses, an alpha of 0.05 was considered and the GraphPad Prism software version 8.0.0 for Mac was used (GraphPad Software, San Diego, CA, USA). All variables were presented as mean and standard deviation. The Shapiro-Wilk test, Levene's test, and Mauchly's test were applied to evaluate the distribution, homogeneity of variance, and sphericity of the data, respectively. To establish significant differences between training groups (CONV, SEBT, and NM) and time (before and after intervention), a 2-way analysis of variance (ANOVA) was used (group × time) with repeated measures. Post-hoc analysis was performed with Tukey's multiple comparison test. The percentage change between comparisons and the effect size (*ES*) were calculated with Cohen's *d*, considering a trivial (0–0.19), small (0.20–0.49), medium (0.50–0.79), or large (0.80 or greater) result.

Ethical approval

The research related to human use has complied with all the relevant national regulations and institutional policies, has followed the tenets of the Declaration of Helsinki, and has been approved by the Ethics Scientific Committee of the Santo Tomás University (Chile) (Folio ID-149-19).

Informed consent

Informed consent has been obtained from all tutors and individuals included in this study and from the participants' legal guardians.

Results

All participants were included in the study analysis as there was 100% adherence to the training plan. The baseline characteristics of the sample can be seen in Table 1. The mean and standard deviation of the pre- and post-intervention variables are reported in Table 2. All the data presented a normal distribution, homogeneity of variance, and sphericity ($p > 0.05$).

In the dominant lower limb, the 2-way ANOVA with repeated measures implied significant interactions between factors (group × time) in the Y-Balance Test: anterior (gl = 2; $F = 6.28$; $p = 0.0076$), posteromedial (gl = 2; $F = 14.07$; $p = 0.0002$), and total index (gl = 2; $F = 6.60$; $p = 0.0063$). Post-hoc analysis can be seen in Tables 2 and 3. Specifically, the SEBT training group presented significant pre- and post-intervention differences in the posteromedial Y-Balance Test ($p = 0.0003$; $ES = 1.53$; % change = 13.4). Furthermore, the NM training group presented significant pre- and post-intervention differences in the anterior ($p = 0.0001$; $ES = 2.19$; % change = 23.9), posteromedial ($p = 0.0001$; $ES = 2.64$; % change = 23.1), and total index ($p = 0.0001$; $ES = 2.11$; % change = 17.8) of the Y-Balance Test. In contrast, in the non-dominant lower limb, the 2-way ANOVA with repeated measures did not report significant interactions between factors (training group × time) ($p > 0.05$).

When comparing the effects of post-intervention training on the dominant lower limb, the post-hoc

Table 2. Y-Balance Test results for each training

Y-Balance Test	Training	Before (mean ± *SD*)	After (mean ± *SD*)	Mean difference	95% CI		*p*	Cohen's *d*	% change
Dominant lower limb									
Anterior (%)	CONV	91.8 ± 7.0	95.4 ± 10.8	–3.6	–14.4	7.3	0.9021	0.39	3.9
	SEBT	87.8 ± 8.8	96.1 ± 7.5	–8.2	–19.1	2.6	0.2092	1.01	9.4
	NM	85.0 ± 8.5	105.3 ± 10.0	–20.3	–31.2	–9.5	0.0001	2.19	23.9
Posteromedial (%)	CONV	97.0 ± 6.9	102.4 ± 9.6	–5.4	–12.3	1.5	0.1855	0.64	5.6
	SEBT	91.2 ± 6.3	103.4 ± 9.3	–12.2	–19.2	–5.3	0.0003	1.53	13.4
	NM	94.9 ± 10.4	116.8 ± 5.5	–21.9	–28.8	–15.0	0.0001	2.64	23.1
Posterolateral (%)	CONV	98.0 ± 12.6	97.0 ± 17.4	1.0	–13.9	15.9	0.9999	0.07	–1.0
	SEBT	85.0 ± 10.2	88.6 ± 13.0	–3.6	–18.5	11.3	0.9711	0.31	4.2
	NM	92.3 ± 10.5	98.7 ± 10.6	–6.4	–21.3	8.5	0.7503	0.61	7.0
Total index (%)	CONV	95.1 ± 7.1	98.3 ± 9.6	–2.6	–11.0	5.7	0.9136	0.31	2.8
	SEBT	88.0 ± 5.7	96.0 ± 9.1	–8.0	–16.4	0.3	0.0636	1.05	9.1
	NM	90.7 ± 8.6	106.9 ± 6.6	–16.2	–24.5	–7.9	0.0001	2.11	17.8
Non-dominant lower limb									
Anterior (%)	CONV	90.4 ± 8.7	100.9 ± 12.2	–10.5	–21.3	0.3	0.0607	1.00	11.6
	SEBT	85.2 ± 3.5	94.1 ± 13.8	–8.9	–19.7	1.9	0.1465	0.88	10.4
	NM	87.7 ± 9.5	98.2 ± 13.5	–10.5	–21.3	0.3	0.0607	0.90	11.9
Posteromedial (%)	CONV	103.5 ± 15.7	110.6 ± 15.8	–7.1	–22.7	8.5	0.7099	0.46	6.9
	SEBT	92.4 ± 8.6	104.4 ± 12.7	–12.1	–27.7	3.6	0.1937	1.10	13.1
	NM	94.6 ± 8.3	114.7 ± 15.1	–20.1	–35.7	–4.4	0.0072	1.65	21.2
Posterolateral (%)	CONV	98.4 ± 10.2	94.5 ± 12.4	3.8	–7.4	15.1	0.8868	0.34	–3.9
	SEBT	89.9 ± 10.1	91.2 ± 13.0	–1.3	–12.53	10.1	0.9991	0.11	1.4
	NM	91.5 ± 9.2	100.6 ± 11.6	–9.1	–20.3	2.2	0.1596	0.87	9.9
Total index (%)	CONV	97.1 ± 9.6	102.0 ± 11.9	–4.7	–15.0	5.8	0.7382	0.42	4.7
	SEBT	89.1 ± 5.7	96.6 ± 11.0	–7.4	–17.8	3.0	0.2650	0.85	8.3
	NM	91.3 ± 6.8	104.5 ± 11.6	–13.2	–23.6	–2.8	0.0080	1.39	14.5

CONV – conventional training, SEBT – Star Excursion Balance Test training, NM – neuromuscular training
The effect size is represented by Cohen's *d*.

analysis showed significant differences between NM training and CONV (p = 0.0001; ES = 1.82; % change = 14.0) and SEBT (p = 0.0001; ES = 1.74; % change = 12.8) in the posteromedial direction of the Y-Balance Test (Figure 1). Similarly, NM training presented significant differences compared with CONV (p = 0.0392; ES = 1.05; % change = 8.8) and SEBT (p = 0.0065; ES = 1.36; % change = 11.3) in the total index of the Y-Balance Test (Figure 1).

Discussion

The purpose of this study was to compare the effects of CONV, SEBT, and NM training on balance control in female artistic gymnasts. The main result was that when comparing the post-intervention effects on the dominant lower limb, it was observed that the NM training generated significant improvement in the balance control in the posteromedial direction of 14% in relation to CONV, and the same NM training presented a 12.8% change over the SEBT training. In addition, in relation to the total index of the dominant lower limb, the NM training caused a change of 8.8% in relation to CONV, and a change of 11.3% compared with the SEBT training. In this way, NM training is the method that produces the best results in artistic gymnasts' balance control evaluated with the Y-Balance Test. To the best of our

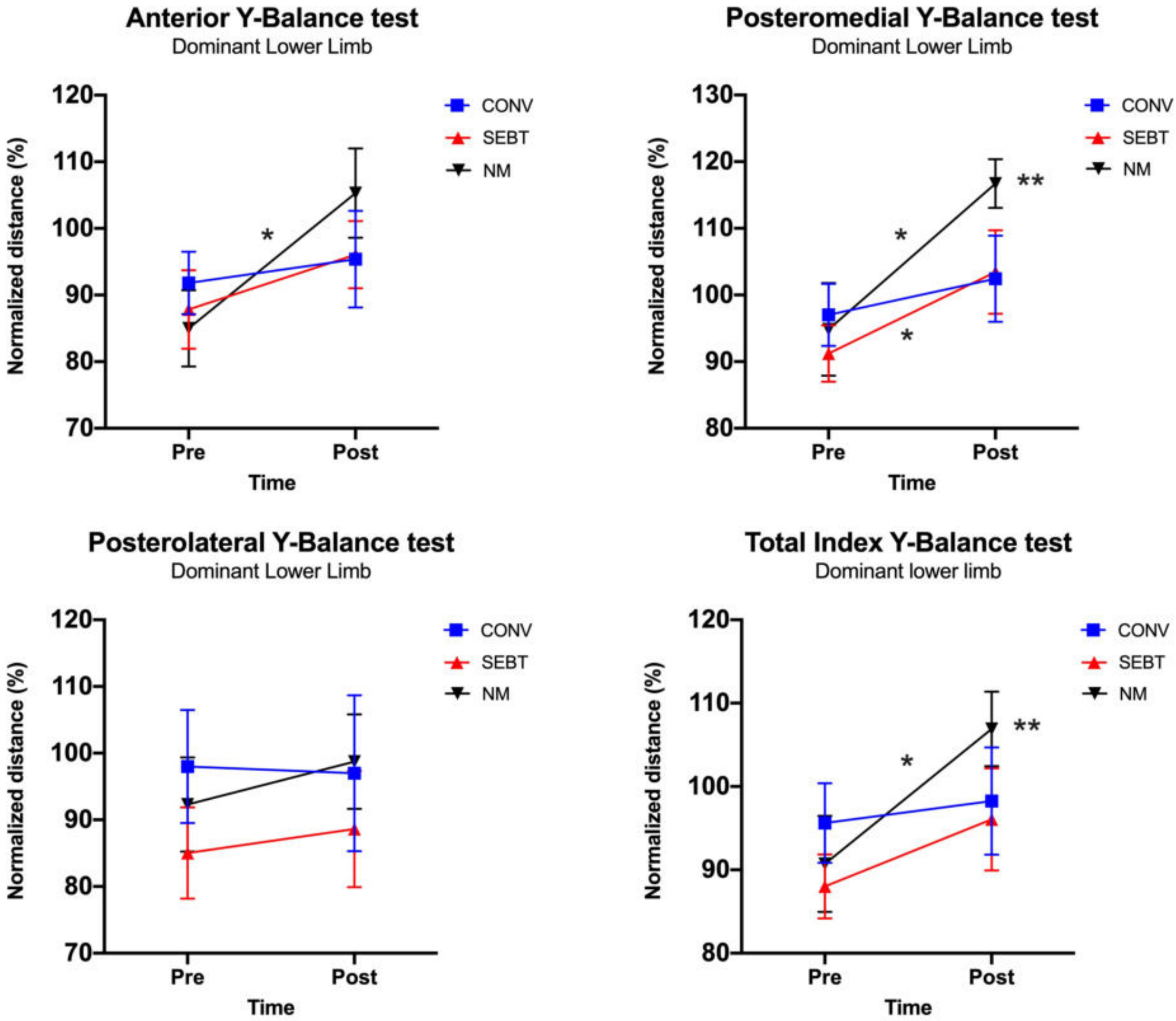
Table 3. Dominant lower limb results of the Y-Balance Test between trainings before and after intervention

Y-Balance Test	Comparison	Mean difference	95% CI		*p*	Cohen's *d*	% change
Anterior (%)	Pre CONV vs. Pre SEBT	4.0	–6.9	14.8	0.8526	0.50	–4.3
	Pre CONV vs. Pre NM	6.8	–4.0	17.7	0.3874	0.88	–7.4
	Pre SEBT vs. Pre NM	2.8	–8.0	13.7	0.9593	0.33	–3.2
	Post CONV vs. Post SEBT	–0.7	–11.5	10.2	0.9999	0.07	0.7
	Post CONV vs. Post NM	–9.9	–20.8	0.9	0.0850	0.95	10.4
	Post SEBT vs. Post NM	–9.2	–20.1	1.6	0.1236	1.05	9.6
Posteromedial (%)	Pre CONV vs. Pre SEBT	5.8	–1.1	12.7	0.1355	0.88	–6.0
	Pre CONV vs. Pre NM	2.2	–4.8	9.1	0.9173	0.25	–2.2
	Pre SEBT vs. Pre NM	–3.6	–10.6	3.3	0.5805	0.42	4.0
	Post CONV vs. Post SEBT	–1.0	–8.0	5.9	0.9970	0.11	1.0
	Post CONV vs. Post NM	–14.3	–21.2	–7.4	0.0001	1.82	14.0
	Post SEBT vs. Post NM	–13.3	–20.2	–6.3	0.0001	1.74	12.8
Posterolateral (%)	Pre CONV vs. Pre SEBT	8.5	–2.8	19.7	0.2157	1.13	–13.2
	Pre CONV vs. Pre NM	6.8	–4.4	18.1	0.4251	0.49	–5.8
	Pre SEBT vs. Pre NM	–1.6	–12.8	9.6	0.9972	0.70	8.6
	Post CONV vs. Post SEBT	3.4	–7.9	14.6	0.9320	0.55	–8.6
	Post CONV vs. Post NM	–6.1	–17.3	5.2	0.5463	0.12	1.8
	Post SEBT vs. Post NM	–9.5	–20.7	1.8	0.1335	0.85	11.4
Total index (%)	Pre CONV vs. Pre SEBT	7.6	–0.8	15.9	0.0879	1.18	–7.9
	Pre CONV vs. Pre NM	4.9	–3.5	13.2	0.4628	0.62	–5.1
	Pre SEBT vs. Pre NM	–2.7	–11.0	5.6	0.9067	0.37	3.1
	Post CONV vs. Post SEBT	2.2	–6.1	10.6	0.9578	0.24	–2.2
	Post CONV vs. Post NM	–8.7	–17.0	–0.3	0.0392	1.05	8.8
	Post SEBT vs. Post NM	–10.9	–19.2	–2.5	0.0065	1.36	11.3

CONV – conventional training, SEBT – Star Excursion Balance Test training, NM – neuromuscular training
The effect size is represented by Cohen's *d*.

knowledge, there are no previous studies comparing training methods through balance control in artistic gymnasts only; generally, the studies were carried out in other sports or in adult patients with various pathologies [7, 15, 21, 24, 25].

It is common to find in the literature research comparing gymnasts with other athletes or a sedentary population, concluding that artistic gymnastics training stimulates the development of balance control and allows an almost perfect stability in relation to other disciplines [26–28]. Currently, an improvement in balance control has been demonstrated through NM training lasting 6–8 weeks, in sessions conducted 3–5 times a week, with an average time of 20 minutes per session, in different athlete and non-athlete populations [13, 15, 17]. Physiologically, the nervous system is in charge of using the information from somatosensory mechanoreceptors [12], causing the skin, joints, ligaments, tendons, and muscles to provide sensory input to the central nervous system to generate a neuromuscular response and thus stabilize the joints [16]. Biomechanically, as the balance control difficulty increases, postural strategies more proximal to the ankle are requested, generating postural adjustments that continually help control balance [29]. In this sense, the inverted pendulum theory is the first to help the sagittal plane to create a compensatory response, locating its axis of rotation at the ankle joint [30]. Also, in the frontal plane, the hip weight change strategy controls the mediolateral balance, transferring the weight of the body from one leg to the other [30, 31]. It could be deduced that the significant improvement observed in NM and SEBT training could be due to a greater request for postural control strategies, described above, in each training session. In this way, these settings resulted in significant improvements in the balance control of artistic gymnasts by training in the different planes of movement and requesting a greater number of



CONV – conventional training, SEBT – Star Excursion Balance Test training, NM – neuromuscular training
* significant differences between pre- and post-intervention times by training (p < 0.05)
** significant differences between trainings in the post-intervention time (p < 0.05)

Figure 1. Comparisons between trainings in the pre- and post-intervention times

neuromuscular responses to the demands of balance control.

Michalski Peres et al. [32] showed that an NM training program applied in volleyball players was effective in increasing the balance control in both lower limbs. In the same context, Vitale et al. [33] applied the Y-Balance Test before and after intervention with an NM training in skiers, showing that the experimental group achieved positive effects in the posteromedial and posterolateral directions, as well as in the total percentage of the Y-Balance Test. As in the team sports noted above, our research has indicated that NM training in individual sports is more effective than CONV, as it leads to improvements in balance control. Possibly, these improvements could increase the performance of artistic gymnasts in the balance beam apparatus and could hypothetically modify the incidence of injuries. However, this assumption must be tested in future research related to the identification of risk factors and prevention of sports injuries.

This research has limitations related to the selection for convenience of the participants because of the small number of gymnasts in order to obtain an adequate sample size. Furthermore, considering only the balance control variable, it is not really known which is the best training to generate global changes in the performance of gymnasts. Future research could consider balance platforms or test batteries that can quantify the balance control in gymnastic positions typical of the sport technique or of the different devices used in competitions. Finally, other essential training methods in gymnastics based on flexibility, strength, and power could be compared, and it could even be taken into account how the development of balance control is affected by other factors, such as the emotional state and muscle fatigue of the subjects [34, 35].

Conclusions

NM training results in significant improvement of balance control compared with CONV and SEBT in female artistic gymnasts. In this context, this study contributes to the comparison among different training methods focused on improving balance control, which is important for a sports improvement approach that leads to optimal performance in artistic gymnastics.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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THE RELATIONSHIP BETWEEN STATIC AND DYNAMIC BALANCE IN ACTIVE YOUNG ADULTS

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ABSTRACT
Purpose. The objectives were to analyse differences of static and dynamic balance between sexes and test the correlations between static and dynamic balance measures.
Methods. The study involved 77 physically active adults, university students (age: 19.1 ± 1.1 years; height: 170.2 ± 9.2 cm; body mass: 64.1 ± 10.7 kg). Static balance was assessed with a force platform under Romberg conditions: a foam surface, eyes open (EOFS); eyes closed (ECFS); challenging the visual-vestibular system (CVVS). The Y Balance Test (YBT) evaluated dynamic balance in anterior, posteromedial, and posterolateral directions. One-way ANOVA examined potential differences between sexes, and the Pearson product-moment test verified the correlations between YBT and static balance measures.
Results. Sex differences were found for all conditions in static balance variables: ellipse area (EA), centre of pressure displacement anteroposterior (DAP) and mediolateral (DML), mean velocity anteroposterior (VAP) and mediolateral (VML), total mean velocity (TV). Females presented a better stability index than males for EOFS (25% DAP, 20% DML, 30% VAP, 21% VML, 19% TV), ECFS (26% DAP, 32% DML, 28% VAP, 32% VML, 32% TV), and CVVS (27% EA, 26% DAP, 19% DML, 17% VAP, 20% VML, 18% TV). Males demonstrated 6% better performance on YBT posterolateral. Correlation tests revealed small to moderate correlations between static and dynamic balance, except for a large positive correlation between YBT anterior and sway area under the CVVS condition [r = 0.54 (0.19; 0.77)] for women.
Conclusions. The findings indicate a weak relationship between static and dynamic balance in controlling posture.
Key words: static balance, force plate, young adults, dynamic balance, Y Balance Test, university students

Introduction

Postural control is a complex motor function based on interactions between multiple dynamic sensorimotor processes whose main functional goals are body stability, postural orientation, and balance [1]. Postural balance is the ability to control one's position while maintaining the centre of gravity within the limits of stability over a base of support. Movement strategies and muscular synergies must be coordinated to stabilize the centre of body mass and minimize the displacements of the centre of pressure (COP) while assuming a quasi-static position or performing daily movements or exercise [1, 2]. Postural balance is considered as the state in which all forces acting on the human body (gravity, muscle strength, and inertial forces) are controlled and the body adopts a desired position, achieves quasi-static balance, or performs a specific movement without losing balance [1–4].

Previous literature related to postural balance is grouped into static and dynamic categories [1, 2]. Static postural stability can be defined as the maintenance of a steady position on a fixed, firm, stable support base. Dynamic postural stability is the ability to transfer the vertical projection of one's centre of gravity around the supporting base using a perturbation on the sup-

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port surface or the individual. Dynamic postural stability can also refer to an individual's ability to maintain their balance after a change in position or location [1, 2, 4]. The central nervous system needs to keep the body position under static and dynamic conditions to maintain balance and produce suitable forces. Proper balance control constitutes the basis for the execution of complex technical movements and improvements in athletic performance [5]. In fact, measuring postural stability and static and dynamic balance is critical to determine predictors of sports performance [6], rehabilitation, injury prevention [7], as well as to assess the efficacy of balance training in the neuromuscular system, balance control, and functional performance among children, adolescents [8], and active young adults [9–11]. Therefore, balance control has attracted the interest of professionals from different fields.

When the goal of a study is to assess static or dynamic posture, the most common posturographic measure used is the COP sway [4]. COP expresses the point of application of the resultant from the vertical force action on the support surface [4]. The literature has cited the importance of analysing COP oscillations while standing on a force plate, as such COP oscillations represent a complex output signal of postural control and the inherent complexity of cognitive, perceptual, and motor processes [4] while challenging the sensory system by altering vision, stance, or surface conditions [4, 12]. The equipment most often used to evaluate COP is a force plate [4, 13–15]. The parameters collected from force plate output (i.e., COP path length, COP excursion, speed of COP change, mean amplitude of COP sway) can represent stability when in a quiet standing position or when maintaining a stable position while carrying out a prescribed movement [4]. However, beyond posturography based on force plate assessments, previous researchers have utilized different instruments to assess dynamic balance. Such instruments include the Balance Error Scoring System [16], the jumping test [17], the Star Excursion Balance Test (SEBT) [18], and the Y Balance Test (YBT) [19, 20]. In fact, dynamic postural control involves various dimensions that also represent the performance of proprioception, the range of motion of lower limb joints, and muscle strength. Researchers have shown that YBT is an effective and objective method for assessing dynamic balance [20–22]. This instrument significantly challenges the postural control system through the completion of a functional task while maintaining a single-leg stance and reaching towards the anterior, posteromedial, or posterolateral direction with the free limb without losing balance [23]. YBT imposes additional demands related to proprioception, range of motion, and strength while the participant remains in a steady, upright position [23].

Although several studies have assessed postural balance in young adults [24, 25], it has not been thoroughly investigated whether static balance reflects dynamic balance. It also remains unclear if sex differences influence this analysis. Hrysomallis et al. [26] were the first to determine the association between static and dynamic balance. Their results indicate a low correlation between the balance scores for the static test (single-limb stance) and the stepping test on an unstable surface. Karimi and Solomonidis [27] instructed the participants to stand on a force plate in a quiet standing position while undertaking various tasks involving their hands. They observed no significant correlation between static and dynamic stability parameters [27]. Sell [28] assessed static postural stability while the participants assumed a single-leg stance (eyes open and eyes closed) and dynamic stability by using the anteroposterior and mediolateral jump. No correlation was found between static and dynamic postural measures.

All the researchers mentioned above studied the relationship between static and dynamic balance, and they all stated that there was no relationship between static and dynamic measures. However, their works varied in terms of methodology – specifically, each study involved different participants and balance tests [26–29]. Most of them implemented a static balance test with a stable surface, though unstable surfaces seem to make the static balance test more challenging and closer to sports contexts for young adults [15, 30]. Additionally, previous research used only one condition to assess static balance test performance; however, it is crucial to evaluate participants' balance when different systems (i.e., visual, proprioceptive [31], and vestibular) are challenged.

There are many balance assessment methods, ranging from simple observations, clinical tests, scales, and posturographic measurements, to integrated evaluation systems of greater complexity. Each method has advantages and limitations and can demonstrate different results with multiple interpretations; this is exacerbated by the lack of consensus regarding which characteristics (e.g., gender) are important [31, 32]. Few studies have examined gender differences in terms of postural stability among young adults as measured by static balance (COP displacement and velocity) and dynamic balance (maximal lower limb reach scores). Additional literature does not seem congruent. Some studies show that women have a better stability index than men [31–33], while others report contradictory results [34, 35]. The relationship between static and dynamic balance control considering sex differences has not been researched. Thus, it is important to know whether males differ from females in terms of balance control and to understand the relationship between gender and balance control measures [31, 32]. A better understanding of the influence of sex on balance control is central to establishing reference data that would allow the detection of balance disorders. Such an understanding might also assist physical activity and health professionals and coaches in prescribing balance training programs.

In short, there is a lack of evidence regarding the relationship between static (force plate with an unstable surface) and dynamic balance (anterior, posteromedial, and posterolateral lower limb reach). An understanding of whether sex influences COP parameters and YBT measures is also lacking. Thus, the purpose of this study was twofold: (i) to analyse the variations in static and dynamic balance between the sexes and (ii) to establish the relationships between static and dynamic balance measures.

Material and methods

Experimental approach to the problem

A cross-sectional design was used to analyse the relationship between static and dynamic balance control measures. The sample consisted of physically active young adults, university students, taking leisure sports courses (1st and 2nd year) who participated in training at least 3 days per week. The participants' anthropometric measures (height, body weight, and 8-site skinfolds) were assessed in a laboratory at a constant environmental temperature and humidity (20–23°C and 50–60%, respectively) before breakfast on a weekday (48 hours after the last training/exercise session) between 8:30 a.m. and 10:00 a.m. All participants wore light clothing and stood barefoot. They were instructed to avoid exercise for a minimum of 24 hours before testing and not to consume alcoholic drinks for a minimum of 48 hours before testing. Static balance control was recorded by using a force plate (Kistler, model 9260AA6, Winterthur, Switzerland). The subjects completed three 30-second trials on a foam surface under 3 different conditions: eyes open (EOFS), eyes closed (ECFS), and challenging the visual-vestibular system (CVVS). The trial order was randomized across the participants to reduce order effects [36].

Before the testing began, each individual performed one practice trial for each condition. Dynamic postural control was assessed by using YBT (anterior, posteromedial, and posterolateral reach directions). Each participant performed 4 experimental practice trials for each direction to become comfortable with performing the task [37]. After 2 minutes of rest, each subject performed 3 test trials in each direction (accounted tests) [20]. The trial order (i.e., anterior, posteromedial, and posterolateral reach directions) was randomized across the participants to reduce order effects [36]. The results of both tests were recorded by an expert with experience in using the necessary equipment; the order of static and dynamic tests was randomized.

Participants and design

A total of 77 physically active young adults voluntarily participated in this study. Their anthropometric characteristics can be found in Table 1. The subjects completed a medical history questionnaire and the International Physical Activity Questionnaire (IPAQ-short form) so that physical activity could be measured. The inclusion criteria in the study were (1) training at least 3 days per week and (2) absence of acute injuries. The exclusion criteria involved (1) previous experience with functional training with unstable platforms or sports that develop balance and proprioceptive skills (e.g., dance, ballet, hockey) and (2) neuromuscular diseases, vestibular disorders, cerebral concussions, chronic lower limb injuries or any pathology or health problem that affects balance and postural control [15, 38].

Anthropometric measures

Each participant's height was measured to the nearest 0.1 cm with a portable stadiometer (Seca 217, Hamburg, Germany). Body weight was determined to the nearest 0.1 kg with mechanical floor scales (Seca 760, Germany). Eight skinfolds were assessed with a Harpenden calliper (British Indicators, Ltd., London, UK) to estimate body fat percentage. All anthropometric variables were measured in accordance with the International Society for the Advancement of Kinanthropometry (ISAK) protocol by a single certified expert

(ISAK Level 2). A test-retest analysis was made to the observer aiming to ensure an appropriate level of reliability. Using 10% of the full data, 3 trials were tested and the reliability level of intraclass correlation tested revealed a value of intraclass correlation coefficient of 0.96, i.e. an excellent reliability level.

Lower limb length

The leg that kicked the ball was considered the dominant leg. Limb length (from the anterior superior iliac spine to the most distal portion of the medial malleolus) was measured in centimetres for 3 trials with a tape measure. The average of the 3 trials was recorded. Leg length was used to normalize YBT excursion distances by dividing the average of 3 maximal reaches by leg length and multiplying the result by 100 [23, 39].

Postural control measures

Static postural control was recorded by using a force plate under 3 different conditions on a foam surface; dynamic postural control was assessed by YBT with anterior, posteromedial, and posterolateral reach directions.

Static postural control

Static postural control under unstable conditions was assessed by measuring COP fluctuations at 1000 Hz with a force plate (Kistler, model 9260AA6). The participants stood barefoot on a foam surface (density: 50 kg/m^3; dimensions: 49 × 39 × 5.5 cm) placed on top of a force plate. They completed three 30-second trials under 3 different conditions: (a) quiet standing, eyes open (EOFS); (b) quiet standing, eyes closed (ECFS); and (c) quiet standing, eyes open, challenging the visual-vestibular system (CVVS) (looking at light signals that changed 10 to 10 seconds: 1^o eye level, 1.80 m off the ground; 2^o looking up, 3.60 m off the ground; 3^o looking to the ground; 4^o eye level). The participants were given 1 minute of rest between the trials [36] and 1 minute of rest between the conditions [15]. The trial order (i.e., EOFS, ECFS, CVVS) was randomized across the subjects to reduce order effects [36]. Each individual could select their preferred stance width [4] and was instructed to stand quietly with their arms hanging at the sides while they placed their head in a normal forward-looking position and focused on a target located at the eye level, approximately 3 m away [15]. Before testing, each participant performed one experimental practice trial for each condition, and then data for 3 trials were collected for each condition. The average of the 3 trials was used for further analysis.

The force and torque signals were amplified (data acquisition system type 5695B, Winterthur, Switzerland) and recorded with commercial software (BioWare, 2812A), which computed the COP time series in the anteroposterior and mediolateral directions. After filtering (fourth-order zero-lag 20 Hz low-pass Butterworth filter), classical sway measures were computed to assess the direction, distance, and velocity of the COP trajectory, with greater values indicating poorer balance. These measures included: sway area, defined as the ellipse area that fits 95% of the COP data points (cm^2); total COP displacement, which represents the overall anteroposterior and mediolateral movement over 30 seconds (cm); and total mean velocity, which signifies the total COP distance travelled in one trial divided by the duration of the trial. Displacement and mean velocity in the anteroposterior and mediolateral directions were also computed. The length versus surface area parameter indicates the ratio of statokinesigram plot length to its area and assesses the energy expended by the subject during the examination [40]. All sway measures were computed through scripts written in the MATLAB code (R2013a, MathWorks Inc., Natick, MA, USA).

Dynamic postural control

Each participant completed YBT for the anterior, posteromedial, and posterolateral directions (Figure 1), modelled in accordance with the methodology described by Plisky et al. [39].

Demonstrations and verbal instruction were given to the subjects to inform them how the test should be performed. YBT was evaluated with a commercially available device (Octo Balance premium version system, Check your MOtion, SKU 1008, Spain). While the participants maintained a single-leg stance, the free limb moved to reach the anterior, posteromedial, and posterolateral directions (maximum possible reach) in relation to the stance foot. The participant then returned to a starting position without losing their balance [10, 39].

Each individual performed 4 experimental practice trials (unaccounted tests) for each direction so that they became comfortable performing the task. After 2 minutes of rest, each participant performed 3 test trials in each direction (accounted tests) [10]. The average of 3 maximal reaches was calculated and recorded. A 10-second rest was provided between the

1 2 3

Figure 1. Y Balance Test: (1) anterior reach direction; (2) posterolateral reach direction; (3) posteromedial reach direction

reach trials [7]. A trial was classified as invalid if the participant removed their hands from their hips, did not return to the starting position, or failed to maintain a unilateral stance on the platform (e.g., if they placed the reach foot on the ground, raised or moved the stance foot during the test, or kicked the plate with the reach foot to gain distance) [7, 39, 41].

Statistical procedures

Descriptive statistics included mean, standard deviation, and 95% confidence interval values. The normality of the sample was tested by using the Kolmogorov-Smirnov test. After confirming the assumption of normality, one-way ANOVA was executed to test the differences between the sexes in static and dynamic balance tests for each condition (EOFS, ECFS, and CVVS). For each condition, the Pearson product-moment (r) test was applied to assess the magnitudes of correlations between YBT measures (anterior, posteromedial, and posterolateral directions) and static balance measures: ellipse area (EA), length versus surface area (LVS), COP displacement anteroposterior (DAP) and mediolateral (DML), mean velocity anteroposterior (VAP) and mediolateral (VML), total mean velocity (TV). The magnitudes of the correlations were inferred on the basis of the following thresholds: 0.0–0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9, very large; > 0.9, nearly perfect [42].

The significance of all statistical tests was set at $p < 0.05$. All statistical analyses were executed with the SPSS statistical analysis software (version 25.0, Chicago, USA).

Ethical approval

The research related to human use has complied with all the relevant national regulations and institutional policies, has followed the tenets of the Declaration of Helsinki, and has been approved by the local ethical committee of the Polytechnic Institute of Viana do Castelo, School of Sport and Leisure, with the code number IPVC-ESDL180801.

Informed consent

Informed consent has been obtained from all individuals included in this study.

Results

The baseline anthropometric characteristics of the participants are presented in Table 1.

Males were taller than females and had a greater body weight and lower body fat percentage ($p < 0.05$).

The descriptive statistics of the static balance test and differences between the sexes are presented in Table 2.

Males were significantly different ($p < 0.05$) than females in terms of static balance measures for all conditions (EOFS, ECFS, and CVVS). Females presented

Table 1. Baseline anthropometric characteristics of the studied population (mean ± *SD*)

Category	Age (years)	Height (cm)	Body weight (kg)	Body fat (%)
Total (*n* = 77)	19.1 ± 1.1	170.2 ± 9.2	64.1 ± 10.7	15.1 ± 5.6
Males (*n* = 48)	19.1 ± 1.1	175.2 ± 7.1*	68.5 ± 10.4*	13.1 ± 5.1*
Females (*n* = 29)	19.0 ± 1.1	162.0 ± 5.9	56.9 ± 6.4	18.4 ± 4.9

* significant differences between sexes (p < 0.05)

Table 2. Descriptive statistics (mean ± *SD*) of static balance test for the overall population and by sex

Category	EA (cm^2)	LVS (cm/cm^2)	DAP (cm)	DML (cm)	VAP (cm/s)	VML (cm/s)	TV (cm/s)
EOFS							
Total ($n = 77$)	4.12 ± 1.82	14.92 ± 5.40	25.37 ± 6.25	40.74 ± 9.39	0.84 ± 0.21	1.36 ± 0.31	1.69 ± 0.30
Males ($n = 48$)	4.15 ± 1.44	14.99 ± 4.82	27.22 ± 6.56*	43.24 ± 9.29*	0.91 ± 0.22*	1.44 ± 0.31*	1.79 ± 0.29*
Females ($n = 29$)	4.06 ± 2.42	14.78 ± 6.45	21.81 ± 3.60	35.96 ± 7.68	0.70 ± 0.12	1.19 ± 0.26	1.50 ± 0.21
ECFS							
Total ($n = 77$)	5.24 ± 2.27	14.26 ± 5.72	30.99 ± 9.96	57.13 ± 16.82	1.05 ± 0.35	1.90 ± 0.56	2.38 ± 0.70
Males ($n = 48$)	5.63 ± 2.31	13.88 ± 5.51	33.51 ± 10.54*	62.76 ± 17.00*	1.14 ± 0.37*	2.09 ± 0.57*	2.61 ± 0.71*
Females ($n = 29$)	4.58 ± 2.07	14.91 ± 6.14	26.69 ± 7.23	47.53 ± 11.49	0.89 ± 0.24	1.58 ± 0.38	1.98 ± 0.43
CVVS							
Total ($n = 77$)	4.19 ± 1.69	13.66 ± 4.68	24.82 ± 6.36	41.24 ± 9.70	0.83 ± 0.22	1.37 ± 0.32	1.75 ± 0.40
Males ($n = 48$)	4.55 ± 1.70*	13.69 ± 4.82	26.14 ± 5.25*	43.87 ± 8.94*	0.88 ± 0.18*	1.46 ± 0.30*	1.86 ± 0.35*
Females ($n = 29$)	3.57 ± 1.51	13.60 ± 4.52	22.57 ± 7.48	36.79 ± 9.47	0.75 ± 0.27	1.22 ± 0.32	1.58 ± 0.43

FS – foam surface, EO – eyes open, EC – eyes closed, CVVS – challenging the visual-vestibular system,
EA – ellipse area (sway area), LVS – length versus surface area, DAP – centre of pressure displacement anteroposterior,
DML – centre of pressure displacement mediolateral, VAP – mean velocity anteroposterior, VML – mean velocity mediolateral,
TV – total mean velocity
* significant differences between sexes ($p < 0.05$)

Table 3. Descriptive statistics (mean ± *SD*) of the Y Balance Test for the overall population and by sex

Category	A (cm)	PM (cm)	PL (cm)
Total ($n = 77$)	54.70 ± 4.97	72.61 ± 7.21	70.02 ± 6.25
Males ($n = 48$)	54.25 ± 4.99	73.75 ± 7.28	71.54 ± 5.83*
Females ($n = 29$)	55.44 ± 4.93	70.73 ± 6.81	67.49 ± 6.20

A – anterior direction, PM – posteromedial direction, PL – posterolateral direction
* significant differences between sexes ($p < 0.05$)

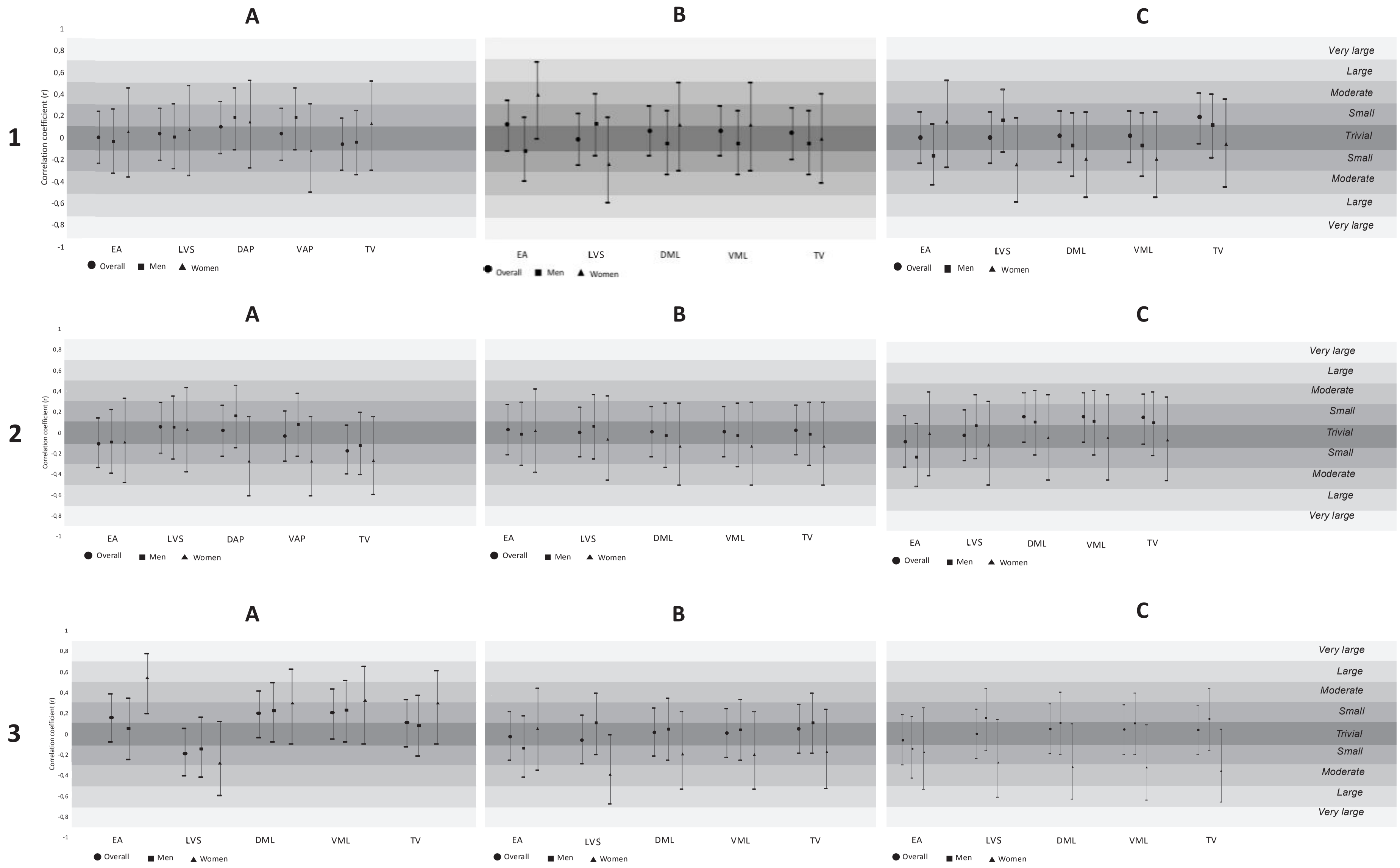
a better stability index compared with males. Specifically, in EOFS, females improved 25% DAP ($p = 0.01$, $d = 0.96$), 20% DML ($p < 0.01$, $d = 0.83$), 30% VAP ($p < 0.01$, $d = 1.11$), 21% VML ($p < 0.01$, $d = 0.86$), 19% TV ($p < 0.01$, $d = 1.10$) as compared with males. In ECFS, the improvements were 26% DAP ($p < 0.01$, $d = 0.72$), 32% DML ($p < 0.01$, $d = 1.00$), 28% VAP ($p < 0.01$, $d = 0.76$), 32% VML ($p < 0.01$, $d = 1.01$), and 32% TV ($p < 0.01$, $d = 1.02$). In CVVS, they equalled 27% EA ($p = 0.02$, $d = 0.60$), 26% DAP ($p = 0.02$, $d = 0.58$), 19% DML ($p < 0.01$, $d = 0.77$), 17% VAP ($p = 0.02$, $d = 0.60$), 20% VML ($p < 0.01$, $d = 0.78$), and 18% TV ($p = 0.01$, $d = 0.73$).

The descriptive statistics of the dynamic balance test are presented in Table 3.

Males were significantly different ($p < 0.05$) than females in terms of YBT test results only for the posterolateral direction (Table 3). Males presented 6% better performance in YBT posterolateral than females ($p = 0.01$, $d = 0.68$).

The magnitudes of correlations between YBT measures and static balance measures under different unstable conditions were also assessed, first for the participants overall and then by sex (Figure 2).

No large correlations were found between YBT and static balance measures for the EOFS condition



EA – ellipse area (sway area), LVS – length versus surface area, DAP – centre of pressure displacement anteroposterior, DML – centre of pressure displacement mediolateral, VAP – mean velocity anteroposterior, VML – mean velocity mediolateral, TV – total mean velocity

Figure 2. Correlation coefficients (95% confidence interval) of Y Balance Test and static balance measures for (1) eyes open, foam surface condition; (2) eyes closed, foam surface condition; (3) challenging the visual-vestibular system

(Figure 2-1) or the ECFS condition (Figure 2-2). Large positive correlations were observed between YBT anterior direction and EA in women [$r = 0.54$ (0.19; 0.77)] for the CVVS condition (Figure 2-3A).

Discussion

This study aimed to compare the static and dynamic balance of men and women and to analyse the relationship between static and dynamic balance measures. Females presented better stability indices than males under all conditions, and small to moderate correlations were found between static and dynamic balance.

Despite the inconsistency of previously reported results, most recent studies have shown that men and women differ in terms of balance. Females seem to have better static balance control than males in anteroposterior and mediolateral stability indices [31–33, 43]. Our data are consistent with previous literature, as female participants presented lower COP displacement and velocity COP displacement values than men in all conditions (EOFS, ECFS, and CVVS), which reflects a better stability index. This observation could be due to anthropometric factors (postural balance seems more influenced by anthropometric factors in men) [43], neuromuscular factors (flexibility/mobility), neurophysiologic factors (processing of inferences); a reason may also be that women often wear high heels, which constantly challenges their balance [32].

However, our observations were different for dynamic balance control. Specifically, YBT assessment revealed that males performed better than females but only in the posterolateral reach direction. This is not consistent with the findings by Ericksen and Gribble [44], who showed that women demonstrated greater reach distances for anterior, medial, and posterior reaches in SEBT. The difference between the 2 studies can perhaps be explained by the fact that Ericksen and Gribble [44] utilized medial and posterior reaches in SEBT, whereas the present study considered the posteromedial and posterolateral reach directions. To the best of our knowledge, no authors have previously compared the reaches of young adult men and women in the anterior, posteromedial, and posterolateral directions.

Previous literature reports a relationship between static and dynamic balance [27–29, 45]. For example, Karimi and Solomonidis [27] concluded that there was no significant correlation between static and dynamic stability parameters. This is because static balance tests assess the stability of participants while in a quiet standing position; meanwhile, dynamic balance tests are more specific and challenging than static tests. The authors suggest that static test performance does not reflect balance task performance [27].

Additionally, Sell [28] examined the relationship and differences between static and dynamic postural stability in healthy, physically active adults. A lack of correlation between static and dynamic balance was found, and the dynamic postural stability scores were significantly higher than static postural stability scores. Dynamic balance tests seem to be more challenging than static balance tests, which could explain the weak relationship between the 2 types of tests [28].

Furthermore, Kim et al. [29] verified the differences between the static and dynamic stability of participants with flexible flatfeet and neutral feet. No relationship was observed between COP speed and YBT scores in either group. In another work, Pau et al. [45] analysed young adults and professional elite soccer players and arrived at the same conclusions (i.e., there was no significant correlation between static and dynamic balance parameters).

Generally, our data show small to moderate correlations between static and dynamic postural balance test performance, which is consistent with most previous research involving active young adults [27, 28] and young athletes [45]. The present results suggest that static balance assessments involving a force plate (with an unstable surface and challenging the visual-vestibular system) seem to differ from YBT assessments of cognitive and motor skills. This difference might be because static and dynamic balance are regulated by different mechanisms [27–29, 45]. In fact, although YBT has been considered a reliable instrument for assessing dynamic balance, some studies have reported that this test requires strength, proprioception, and joint mobility in addition to balance [39].

Another possible reason for the present result is related to the different requirements concerning muscle strength and muscular activation to perform static and dynamic tests. It seems that to maintain body control during YBT (which involves anterior, posteromedial, and posterolateral maximal reaches), participants need neuromuscular control, which is gained through proper joint positioning and proper strength in the principal musculature [23, 46]. Additionally, during a static postural control task, the objective is to minimize COP displacement, which is derivative of the vertical ground reaction force [23, 46]. Meanwhile, the goal of YBT is to assess dynamic postural control by forcing participants to disturb their balance as they try to reach maximum distances while maintaining unilateral support [23, 46].

YBT movement patterns differ from the movements carried out during everyday activities [46], as people do not commonly challenge their balance to the joint range of motion required during YBT. In fact, these static and dynamic tests seem to be different, as they require different skills. YBT is considered a dynamic balance test that demands specific skills that differ from those inherent in the static balance test.

The present data also showed a large and positive correlation between the YBT anterior direction and sway area for the CVVS condition in females. No other significant correlations were found between static and dynamic balance in males or females. This observation suggests that females with higher performance in YBT anterior (i.e., females with better dynamic balance) tend to present higher values in the sway area (i.e., they have weaker static balance) when instructed to move their head to challenge their visual-vestibular system.

The lack of previous evidence from studies with a similar objective makes it difficult to provide a general discussion of the results.

Limitations of the study and future directions

There are several limitations in the present study. The sample was composed of active young adults with different sports experiences. Therefore, before the static and dynamic balance assessment, it would be important to characterize the type, frequency, and intensity of the sports activity, as well as divide the participants in accordance with these factors.

The study investigated the relationship between static and dynamic balance. For the static balance assessment, the subjects performed the test with bipedal support, and for YBT, they were forced to use unipedal support. This may bias the results and discussion as the lower-extremity, trunk, and core muscular activation and joint stability/mobility during each YBT direction reach was not controlled. It should be interesting to investigate the differences between YBT measures in muscular activation and joint stability/mobility in the same sample (young adults undertaking sports activity). Also, it will be noteworthy to verify the influence of mobility program training on the YBT performance, and the influence or contributions of the proximal and distal joints range of motion.

Practical applications and study relevance implications

– The balance and postural control assessment can help to understand why balance disorders occur and how to prevent injuries.

– The small to moderate correlations between static and dynamic measures of balance and postural control indicate that people present different responses when attempting to maintain postural balance stability. Static and dynamic balance appear to be independent of each other; thus, they might need to be tested and trained complementarily. Dynamic balance tests seem to be more specific and challenging than static tests, particularly for young adults.

– Static and dynamic balance measures are useful for assessing both balance and postural control. However, we suggest that tests should be carefully chosen to ensure that they are appropriate for the study population of interest.

Conclusions

This study reveals small to moderate correlations between static and dynamic measures of balance and postural control, suggesting a weak relationship between static and dynamic balance test performance.

However, the positive correlation between YBT and sway area implies that females with high YBT anterior performance (i.e., good dynamic balance) tend to present a greater sway area (i.e., poor static balance) when instructed to move their head and challenge their visual-vestibular system.

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Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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INFLUENCE OF A SMARTPHONE USE ON DYNAMIC BALANCE IN HEALTHY ADOLESCENTS

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ABSTRACT
Purpose. The aim of the study was to detect the immediate and late effects of using a smartphone for 30 consecutive minutes on dynamic balance in healthy adolescents.
Methods. Overall, 96 healthy adolescents of both genders, aged 15–18 years, were randomly assigned to the study and the control group. The subjects in the study group used a smartphone for 30 consecutive minutes; smartphones were not allowed in the control group. A Biodex system was used to assess the dynamic balance initially, as well as immediately after and 1 hour after the intervention.
Results. MANOVA test revealed that there were statistically significant differences in the overall stability index and anteroposterior stability index (p = 0.002 and 0.04, respectively), with a statistically insignificant difference in the mediolateral stability index (p = 0.46) within the study group. Significant differences were observed in the immediate measurements of both overall stability index and anteroposterior stability index (p = 0.0001 and 0.03, respectively), while statistically insignificant differences were noted in the measurements of mediolateral stability index between the groups.
Conclusions. The dynamic balance decreased after 30 consecutive minutes of smartphone use, so care should be taken to avoid accidents while walking or performing other daily activities. This effect, however, disappeared 1 hour later.
Key words: smartphone, dynamic balance, adolescent

Introduction

The smartphone has already become a part of adolescents' daily life; it offers many conveniences, but its negative effects should not be overlooked. Adolescents turn out to be habitually dependent on smartphones and when they do not use them, they feel nervous [1]. Smartphone usage influences clients both physically and mentally. A longer span of smartphone use causes a consistent mechanical load on the muscles and ligaments, which can result in musculoskeletal side effects as undeniable irritation of neck and shoulders because of expanded pressure brought about by a persistently forward neck posture [2].

The increase in the using rate of a smartphone, especially at young age, constitutes a high-risk factor for many physical health problems. Several symptoms reported at follow-up were greatest among smartphone users; these include visual exhaustion, myalgia, neural brokenness, tension, visual and auditory inattentions [3–6]. Adolescents can be more vulnerable to the adverse effects of smartphone use because they are

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uncritically receptive and easily adapted to new technologies, which can cause addictions similar to those of substances [7].

The balance study is essential for different ages, genders, races, and athletic abilities. Good posture, including static and dynamic balance, is very important for the adequate performance of many daily basic and recreational activities, so any balance alterations may lead to difficulties in the activates of daily living [8].

Different methods have been developed to assess posture stability, starting from the Timed Up and Go test, implemented by Mathias in 1986, which constitutes the shortest, simplest clinical balance test, though it is less objective [9]. After that, a forward-reaching test was used to assess the dynamic balance by measuring the maximum distance of reaching forward with either an arm or foot while remaining stable. That was followed by arm raising tests to measure a person's ability to maintain balance when raising and lowering the arms [10]. Another developed test to assess dynamic stability was the stepping test: the subject is asked to step a foot on and off a block as many times as possible in a detected time [10].

The methods of postural stability assessment should consider the effort needed to maintain the stability of dynamic balance. The total value of the stabilizing torque must counteract the destabilizing torque due to gravity in quiet standing [11]. The NeuroCom postural stability balance master systems have low to moderate reliability outcomes in measuring dynamic balance [12] but the assessment of postural stability with the Biodex Balance System constitutes the best selection for dynamic balance evaluation as it provides a valid, reliable, and repeatable objective assessment of balance on stable and unstable surfaces; it is also applied for training services. The device offers visual feedback of a patient's ability to control the body posture and enhance regaining the balance [13].

Another method to evaluate dynamic balance is the wobble board, which offers different biomechanical and neuromuscular control strategies that are more significant than balance tests on a firm surface. Differences in control strategies have implications for the understanding of various rehabilitation programs mechanisms [14]. In addition, balance performance measurement methods include static and dynamic balance tests in upright position standing which consider anthropometric characteristics, sex, and lower limb strength; these differently influence the Y Balance Test measures, regardless of limb dominance. The static and dynamic balances have been determined bilaterally by the Single Leg Stance Balance Test and the Star Excursion Balance Test, respectively. The latter provides scores for the anterior, posterolateral, and posteromedial directions, as well as an overall composite score [15].

Proper dynamic balance control is the basis in the achievement of motor skills. It mainly involves multiple strategies to minimize the displacements of the centre of gravity; these strategies are needed for numerous daily activities [16]. Many previous studies have discussed the effects of smartphone use on neck pain, cervical posture, muscle fatigue, gait, and many other aspects [17–19], but limited research has referred to the influence on dynamic balance and, to our knowledge, there are no studies concerning adolescents. Therefore, this study aimed to investigate the influence of smartphone use on dynamic balance in healthy adolescents. It was hypothesized that there was no influence (immediate or late) of smartphone use on dynamic balance in healthy adolescents.

Material and methods

Participants

A randomized controlled trial was conducted between August 2019 and October 2019 at the Laboratory of Biomechanics, Faculty of Physical Therapy, Modern University for Technology and Information, Cairo, Egypt. A total of 96 healthy adolescents of both genders (36 males and 60 females) participated in the study; they were recruited through online social media. The inclusion criteria involved age of 15–18 years, normal body mass index in accordance with the growth chart [20], and having been a smartphone user for at least 1 year. Excluded were all subjects who had a history of a disease affecting balance or neuromuscular control (cerebellum, basal ganglia, middle ear, proprioceptors), a musculoskeletal disorder, or even a complaint about any lower limb weakness. Each participant received a verbal explanation of all test procedures and applied them once before starting the proper test to become familiar with them. The subjects were randomly assigned, by coin tossing, to 2 groups (study and control group) (Figure 1).

Procedures

A Biodex system (Biodex Medical Systems Inc., Shirley, NY, USA, serial no: 13020193) was used for

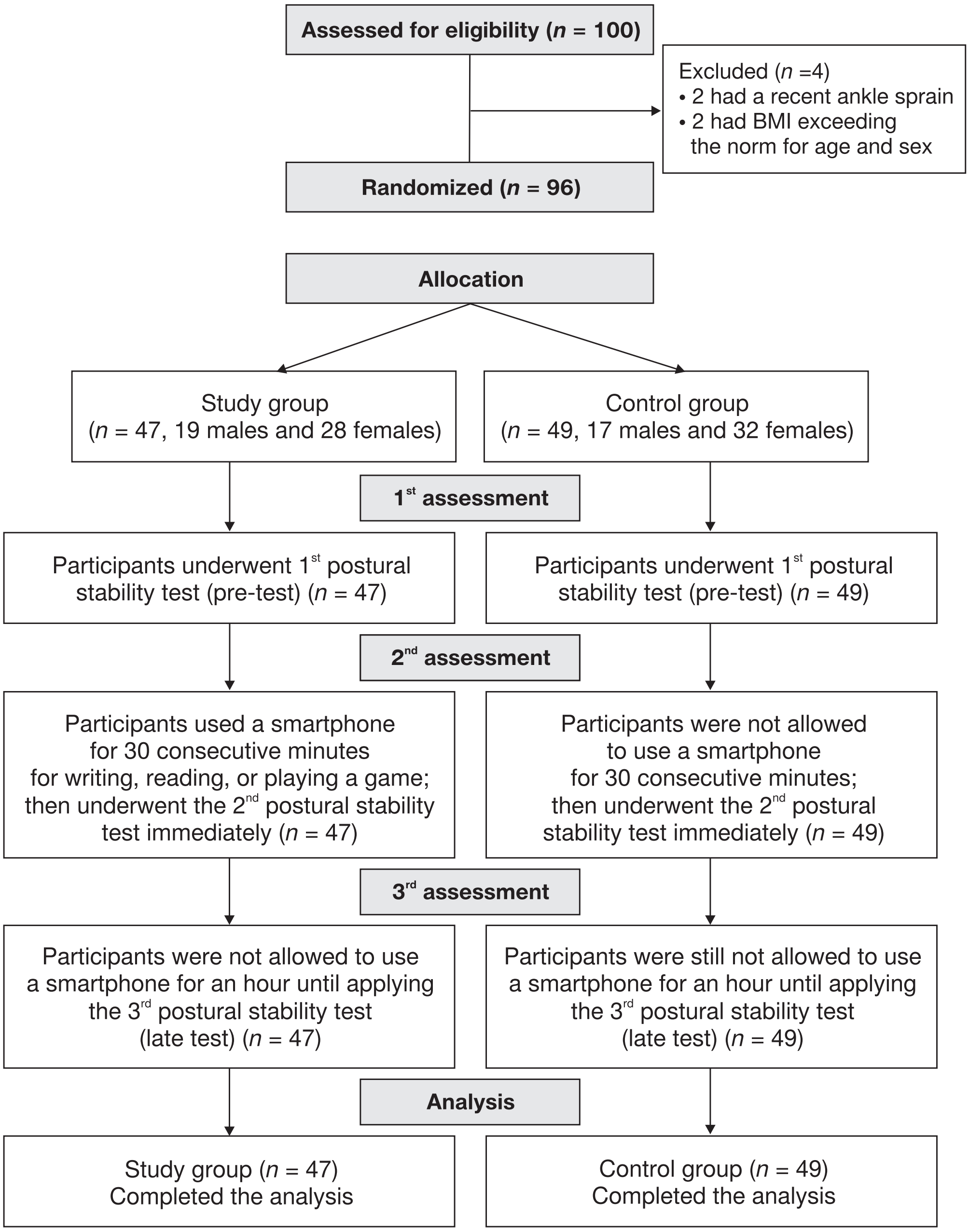

Figure 1. The study flow chart

dynamic balance assessment. The components of Biodex include a circular foot platform with a diameter of 21.5 inches which permits 20° tilting in all directions, a height-adjustable screen, height support rails, and a printer. The device allows static balance measurements plus 12 levels of dynamic balance measurements. Dynamic balance was assessed by the ability to control the tilting angle of the Biodex platform, which was reported as a stability index including the anteroposterior stability index (APSI), the mediolateral stability index (MLSI), and the overall stability index (OSI). Increasing values of the indices demonstrate a significant amount of sway, which implies a balance problem [21]. The Biodex system constitutes a valid and reliable objective measurement tool for dynamic balance assessment [22]. Regarding the smartphone, Galaxy Note 3 (SM-N900S, Samsung Electronics Co., Ltd., Seoul, Korea) was used (with Internet access connection).

The test procedures started by entering the participant's personal data (name, age, and height); then, the subject was asked to stand barefoot on the Biodex platform. After selecting the postural stability test, the level of stability was adjusted at the sixth level for 30 seconds (test period). When starting the test, the participant was asked to control their balance as much as possible with arms held at the sides, standing on both feet, with eyes open, and being guided by the visual feedback on the screen (the individuals were instructed to maintain the cursor in the centre of the circle displayed on the screen as much as possible). The measuring data included OSI, APSI, and MLSI. A trial was applied for familiarization with the test without recording its results; then, 3 recoded trials were conducted for each measurement, and the mean was obtained. A pre-intervention test was performed for all participants. In the study group, the individuals were allowed to use a smartphone for writing, reading, or playing a game for 30 consecutive minutes. Then, the immediate post-intervention test was performed. After that, the participants were not allowed to use a smartphone for an hour until conducting the late posture stability test. In the control group, the subjects were not allowed to use a smartphone for 30 minutes. Then the immediate post-intervention test was performed. After that, the participants were still not allowed to use a smartphone for an hour until conducting the late postural stability test (Figure 1).

Statistical analysis

All statistical calculations were carried out by using the IBM SPSS computer program, version 22 (IBM Corporation, USA). The sample size calculations were performed with the G*Power software (version 3.0.10). OSI was chosen as the primary outcome measure, while APSI was the secondary outcome. The effect size of OSI was estimated to be medium (0.25). The generated sample size of at least 40 participants per group would be required. Allowing for a 20% dropout rate, it was necessary to reach a total sample of a minimum of 96 participants. The test of homogeneity (Levene's test) showed that all data were homogenous. The test of normality (Shapiro-Wilk test) demonstrated that the data were normally distributed, so the parametric test was used (unpaired *t*-test to compare demographic data between groups and MANOVA to compare measurements within and between groups). The chi-squared test was applied for gender distribution, and the least significant difference test served for post-hoc comparison. The value of $p < 0.05$ was considered statistically significant.

Ethical approval

The research related to human use has complied with all the relevant national regulations and institutional policies, has followed the tenets of the Declaration of Helsinki, and has been approved by the ethical

Table 1. General demographic data

Parameter	Number of participants		Age (years) ($\bar{x} \pm SD$)	Body mass index (kg/m^2) ($\bar{x} \pm SD$)	Weight (kg) ($\bar{x} \pm SD$)		Height (cm) ($\bar{x} \pm SD$)		Smartphone use (years) ($\bar{x} \pm SD$)
	Males	Females			Males	Females	Males	Females	
Study group	19	28	16.3 ± 1.16	21 ± 1.5	62.5 ± 3.03	54.5 ± 3.03	171.5 ± 3.03	167 ± 1.49	3.9 ± 0.88
Control group	17	32	16.4 ± 1.26	20.6 ± 1.43	62.2 ± 4.8	54.6 ± 4.14	173 ± 5.31	166.7 ± 1.77	3.7 ± 1.16
t			0.18	0.61	0.17	0.06	0.78	0.41	0.43
p			0.86	0.55	0.87	0.95	0.45	0.69	0.67
Chi-square	0.34								
p	0.65								

Table 2. Postural stability indices (mean ± standard deviation)

Parameter	Overall stability				Anteroposterior stability				Mediolateral stability			
	Pre-intervention	Immediate	Late	*p*	Pre-intervention	Immediate	Late	*p*	Pre-intervention	Immediate	Late	*p*
Study group	1.1 ± 0.27	1.6 ± 0.37	1.28 ± 0.6	0.002	0.72 ± 0.26	0.94 ± 0.26	0.83 ± 0.34	0.04	0.75 ± 0.21	0.7 ± 0.27	0.69 ± 0.3	0.46
Control group	0.98 ± 0.37	1.17 ± 0.41	1.01 ± 0.55	0.2	0.65 ± 0.15	0.76 ± 0.29	0.67 ± 0.26	0.61	0.77 ± 0.26	0.7 ± 0.27	0.69 ± 0.3	0.5
p	1	0.001	0.18		0.71	0.03	0.19		1	1	1	
Effect size		$\eta^2 = 0.88$				$\eta^2 = 0.64$				$\eta^2 = 0.08$		

Table 3. Pairwise comparisons

Time X	Time Y	Mean difference (X–Y)	Slandered error	p	95% confidence interval for difference	
					Lower bound	Upper bound
Pre-intervention	Immediate	0.37*	0.03	< 0.001	0.31	0.43
	Late	0.36*	0.02	< 0.001	0.32	0.41
Immediate	Late	–0.012	0.02	0.560	–0.06	0.03

* $p < 0.05$

committee of the Faculty of Physical Therapy, Cairo University, Egypt (No. P.T.REC/012/002420). The study has been registered in the Pan African Clinical Trials Registry (No. PACTR201908659527420.

Informed consent

Informed consent has been obtained from all individuals included in this study and their legal guardians.

Results

General demographic data

The mean age, body mass index, weight (males and females), height (males and females), and duration of smartphone use (± standard deviation) revealed that there were statistically insignificant differences between groups (t = 0.18, 0.61, 0.17, 0.06, 0.78, 0.41, and 0.43; p = 0.86, 0.55, 0.87, 0.95, 0.45, 0.69, and 0.67, respectively) (Table 1).

Postural stability test

There were significant effects of groups and measurements (p = 0.0001, F = 132.88; p = 0.0001, F = 68.39, respectively, with hypothesis degree of freedom = 2). An insignificant interaction was observed between groups and measurements (p = 0.19, F = 1.75). The intra-group comparisons in the study group showed statistically significant differences in both OSI and APSI (p = 0.002 and 0.04, respectively) and a statistically insignificant difference in MLSI (p = 0.46).

All postural stability indices (OSI, APSI, and MLSI) presented statistically insignificant differences (p = 0.2, 0.61, and 0.5, respectively) within the control group.

The inter-group comparisons of both OSI and APSI revealed statistically insignificant differences in the pre-intervention and late measurements (p = 1, 0.18, 0.71, 0.19, 1, and 1, respectively). There were significant differences in the immediate measurements of both OSI and APSI (p = 0.0001 and 0.03, respectively) and a statistically insignificant difference in MLSI (p = 1). Partial eta squared was used to detect the effect size and it was found to be large for both OSI and APSI (η^2 = 0.88 and 0.64, respectively), while it was small for MLSI (η^2 = 0.08) (Table 2).

Post-hoc least significant difference

Pairwise comparisons showed statistically significant differences between the pre-intervention measurement and both the immediate and late measurements (p < 0.001 for both). There was a statistically insignificant difference between the immediate and late measurements (p = 0.56) (Table 3).

Discussion

The study showed statistically significant differences in both OSI and APSI (p = 0.002 and 0.04, respectively), as well as a statistically insignificant difference in MLSI (p = 0.46) within the study group. Statistically insignificant differences were observed in all postural stability indices (OSI, APSI, and MLSI; p = 0.2, 0.61, and 0.5, respectively) within the control group. The study also revealed statistically insignificant differences in the pre-intervention and late measurements (p = 1, 0.18, 0.71, 0.19, 1, and 1, respectively) for all postural stability indices, while there were statistically significant differences in the immediate measurements of both OSI and APSI (p = 0.0001 and 0.03, respectively) and a statistically insignificant difference for MLSI (p > 0.05).

Regarding the significant decrease of OSI and APSI in the study group immediately after the smartphone use and the disappearance of this negative effect after 1 hour, these detected changes in the dynamic balance may be due to the influence of the smartphone on the information that flows through the interacting vestibular system, visual and proprioception information in the central nervous system [23]. Also, the electromagnetic waves of the smartphone result in a balance disturbance that occurs owing to the affection of visual and auditory factors. Because the afferent information required for normal body balance depends on superficial sensory perception and proprioception, any loss in these different body structures leads to increasing posture sway [19, 24].

The present study revealed statistically significant differences between the study and control groups in both OSI and APSI in the immediate measurements. These findings confirm that using the smartphone results in postural adjustments of neck and shoulder. This was discussed by Brown and Palvia [25], who concluded that neck pain and muscle tension after a smartphone use could change the sensitivity of neck proprioception as a result of muscle fatigue and increased loading of the neck and shoulder muscles due to the repeated motions of hands, wrists, and arms, all these factors affecting dynamic balance ability. The significant affection of the balance score in smartphone users may also be attributed to a disturbing cervical afferent function. Sustained muscle tension changes the sensitivity of neck proprioception, which affects the dynamic balance ability and increases posture sway [26]. A previous study found that cervical muscle fatigue caused a decrease in the dynamic balance owing to enhanced muscle spindle discharge, which occurred with muscle fatigue and obstructed the afferent feedback input to the central nervous system; this brought about changes in the proprioceptive and kinaesthetic properties of joints, which had a negative effect on the postural control ability [27].

Furthermore, Roy [28] showed that the major cause of balance alteration after an isometric contraction of cervical muscles appeared to be proprioceptive interference, which in turn increased the velocity of sway during quiet standing. Suboccipital muscle fatigue may change balance because of the activation of tonic gamma motor neurons due to the accumulation of metabolites during muscle contraction. The accumulation of potassium, as well as arachidonic and lactic acids leads to positive feedback, increased excitation of muscle spindles, and gamma motor system hyperactivity.

The study findings agreed with those presented by Cho et al. [29], who observed that using a smartphone could increase the instability of the dynamic postural balance. Therefore, smartphone use in such situations as walking or driving a vehicle should be discouraged. Also, Lamberg and Muratori [30] indicated that smartphone use had negative effects on gait pattern and parameters, as it decreased walking speed by 33% and increased lateral deviation during gait by 61% owing to reduced concentration.

Surprisingly, the current study revealed a significant immediate influence of smartphone use on OSI and APSI; there was also an insignificant influence on MLSI. This can be explained by the fact that balance is a complex motor control task involving the detection and integration of sensory information to assess the position and motion of the body in space and the execution of appropriate musculoskeletal responses to control body position within the context of the environment and task. Thus, balance control requires the interaction of the nervous and musculoskeletal systems and contextual effects [31, 32]. Although all the significant influences of the smartphone use on the dynamic balance appeared immediately, all disappeared after 1 hour, which implies that this impact is transient and improves through the interaction of body components, which helps to maintain balance by sensory detection of body motion (visual, vestibular, and somatosensory inputs), integration of sensorimotor information within the central nervous system, and execution of musculoskeletal responses [19, 33].

In contrast with the results found regarding mobile device use, researches examining the relation between physical activity, posture stability, and phone usage reported negative associations between mobile device use and physical activity: greater mobile device or application use was associated with declined physical activity and posture stability [34, 35]. Dual tasking while using different functions of a smartphone is widespread in the social life; it reduces the cognitive ability and thus affects postural control [36].

In addition, dynamic balance decreased in all 3 directions while playing games, sending messages, Web surfing, and listening to music using a smartphone. Playing games decreased cognitive ability most significantly, which resulted in the greatest decrease in dynamic balance. This was followed by sending a message, Web surfing, and listening to music [16].

Therefore, the hypothesis of immediate effect was rejected because the smartphone decreased the dynamic balance, while the hypothesis of late effect was accepted because the immediate decrease of dynamic balance was transient and the balance was regained an hour after smartphone use. Smartphone users should not perform activities that need a good balance immediately after using their smartphones for a long period (30 minutes). Also, trainers and sports educators should inform athletes to stop using their smartphones directly before sports activity as it could affect their dynamic balance during the participation in different sports.

Limitations

Limiting the study sample size to only 96 subjects may affect generalization. The study is also limited to a specific age (adolescent) and to 30 minutes of smartphone activities, so more research is needed for different ages and periods of using a smartphone (shorter and longer than the investigated 30 minutes).

Conclusions

From the obtained results of this study, we conclude that dynamic balance could be decreased immediately after 30 consecutive minutes of using a smartphone for reading, writing, or playing games. Care should be thus taken to avoid any accidents while walking, sports participation, or other daily activities. This negative effect on dynamic balance can, however, disappear after 1 hour.

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Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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RELIABILITY OF ASSESSING BALLET DANCERS' POSTURAL STABILITY IN THE UNSHOD AND THE EN POINTE RELEVÉ POSITION WITH A SMARTPHONE APPLICATION

original paper
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ABSTRACT
Purpose. This study aimed to verify the reliability of estimating ballet dancers' postural stability during the unshod and the en pointe relevé position with a smartphone application
Methods. The participants (13 ballet dancers, 22.4 ± 2.5 years of age) were tested in the unshod and the en pointe relevé position (YMED Balance Test application, smartphone secured at the L5 level for centre of mass approximation, 10 trials for each condition, 10 seconds per trial, 2-minute intertrial break, arms relaxed at bodyside, gaze fixated at an eye-level target, preferred feet width and orientation). Paired t-tests examined the inter-condition differences. Relative (intraclass correlation coefficient, ICC) and absolute (standard error of measurement, SEM, SEM%) reliability indices (for accumulated and paired trials) were computed for each condition (SPSS software v. 26.0, $p < 0.05$).
Results. The total balance score and all centre of mass spatial measures indicated worse postural stability in the en pointe condition ($p < 0.05$), with no significant temporal differences ($p > 0.05$). The total body balance score was the most reliable measure (good to excellent ICCs, low to moderate SEM%) with a minimum of 8 trials ensuring reliability in both the unshod and the en pointe relevé positions.
Conclusions. Taken a minimum of 8 trials and the measure of total balance score, we may obtain a reliable estimation of ballet dancers' postural stability in the unshod and the en pointe relevé position by using the YMED Balance Test smartphone application.
Key words: balance, centre of mass, tip-toe stance, accelerometer, inertial sensors

Introduction

The postural stability of ballet dancers has been evaluated in a variety of stances [1–5]. The en pointe relevé position is an ultimate postural stability challenge for ballet dancers owing to the extreme ankle joint configuration (full plantar flexion) [6], which together with the very small base of support provided by the pointe shoes induces a very sensitive equilibrium and an increased falling risk [1]. Nevertheless, the en pointe relevé position is not common among the relevant postural stability studies in ballet dancers. Evaluation of ballet dancers' postural stability in the en pointe relevé position allows to determine the skill level and may contribute to specified training technical recommendations [2].

The gold standard of postural stability evaluation in a laboratory setting is the force plate in general population studies [7] but also among ballet dancers [2, 5], followed by elaborated motion capture systems [6, 8, 9]. In recent years, wearable sensors based on miniaturized inertial measurement units (typically including accelerometers and gyroscopes) have increasingly been used in postural stability studies [7, 10–12], ballet dancers studies inclusive [3, 13].

Although the laboratory devices provide a state-of-the-art quantitative evaluation of postural stability, they involve a high cost in both money and time, the evaluation procedure is complex, and a field setting is often not applicable because of the limited portability of the devices [14–16]. Smartphones can be regarded as a solution for overcoming the limitations of laboratory-based

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assessments. Portability, together with their built-in accelerometers, have turned smartphones into a major potential for objective and convenient (easy, portable, and affordable) postural stability assessment in a field setting [14, 16–18]. In such a case, the reliability of the smartphone application itself, as well as of the particular standing position and the examinee specificity remains an issue of concern [9, 15, 17]. Thus, the purpose of this study was to evaluate the reliability of determining ballet dancers' postural stability during the unshod and the en pointe relevé position by using a smartphone application.

Material and methods

Sample

Thirteen young women (age: 22.4 ± 2.5 years, body height: 162.6 ± 5.95 cm, body mass: 54.62 ± 8.03 kg) experienced in classic ballet dance (11.8 ± 4.1 years), as well as in the en pointe relevé position (5.6 ± 3.1 years) participated in the study. They all used their regular pointe shoes as the time of use does not appear to affect stability [19]. The participants were free of musculoskeletal injuries or vestibular disorders that would potentially affect their postural stability.

Smartphone application

The YMED Balance Test application for an Android-based smartphone (Xiaomi Redmi Note 5, released in February 2018, https://www.mi.com/global/redmi-note-5/specs/) was used in the present study. The Xiaomi Redmi Note 5 smartphone has an accelerometer sensor resolution at 0.0024 m/s^2, which is a common one among the smartphone accelerometer sensors (https://phyphox.org/sensordb/). The application (developed in 2012 by Physiotools YMED, http://physiotool.blogspot.com/2011/) uses only the accelerometer sensor embedded in smartphones and is available from the Google Play Store (https://play.google.com/store/apps/details?id=com.hyunc.rehatrain.balancecheck&hl=el&gl=US).

The YMED Balance Test was selected from among 3 smartphone applications (Balance Test, Sway, and YMED Balance Test) [17]. The selection criteria were the low cost together with the specificity of the offered tasks, which allows the assessment of static postural stability through an easy and non-expensive software acquisition. Specifically, among the 3 smartphone applications, the Balance Test by Slani is free of cost but designed as a balance board test, and the Sway has to be paid by a minimum of 50 profiles per year ($4.50 per profile) [17]. Instead, the YMED Balance Test can be used completely through a final $8.00 payment, without having to pay again in the future [17]. Furthermore, it is reported to provide values of moderate to high relative reliability with intraclass correlation coefficients (ICCs) ranging from 0.62 to 0.91 [17], and has been validated against the Biodex Stability System with a rather low systematic error at 0.01–0.08 [15].

Data collection procedure

The YMED Balance Test offers 4 types of tasks (vestibule, sitting, knee, balance board) with a 10-second data collection period. In their validation study against the Biodex Stability System, Park et al. [15] report its sampling frequency as 1 dot every 60 ms and 1000 dots per minute, which infers a sampling frequency of 16.6 Hz. Since its first release in 2012 (personal communication with the developer at yhc0869@hanmail.net), the YMED Balance Test has been updated and the sampling frequency is 100 Hz (resulting in 1000 dots for the standardized 10-second sampling duration). The calibration of the accelerometer sensor of the smartphone was tested by using the RedPi Apps Tools (available from the Google Play Store at https://play.google.com/store/apps/details?id=redpi.apps.accelerometercalibrationfree&hl=en&gl=US). Also, the procedures described by Ma et al. [20] were applied for static bias testing.

The vestibule task of the YMED Balance Test was used in both the unshod and the en pointe relevé conditions. Data collection began via the start button, initiating the 5-second zeroing calibration procedure (accompanied with a visual 5-4-3-2-1-START countdown), which is immediately followed by the 10-second data collection. The first centre of mass (CoM) point immediately after the completion of the 5-second calibration procedure defines the zero CoM position (personal communication with the developer). After data collection, a report is saved on the mobile phone including the total balance score, as well as octadrant-based directional variables (Figure 1D). In both the unshod and the en pointe conditions, 3 familiarization trials were allowed per condition. Ten trials were performed in each condition (2-minute break among trials, 5-minute break before the main data collection procedure). In case the participants failed to maintain their relevé position throughout the 10-second data collection period, the trial was repeated. The subjects were instructed to stand in front of a ballet bar (typical height), place their hands on the bar, and remain in full contact

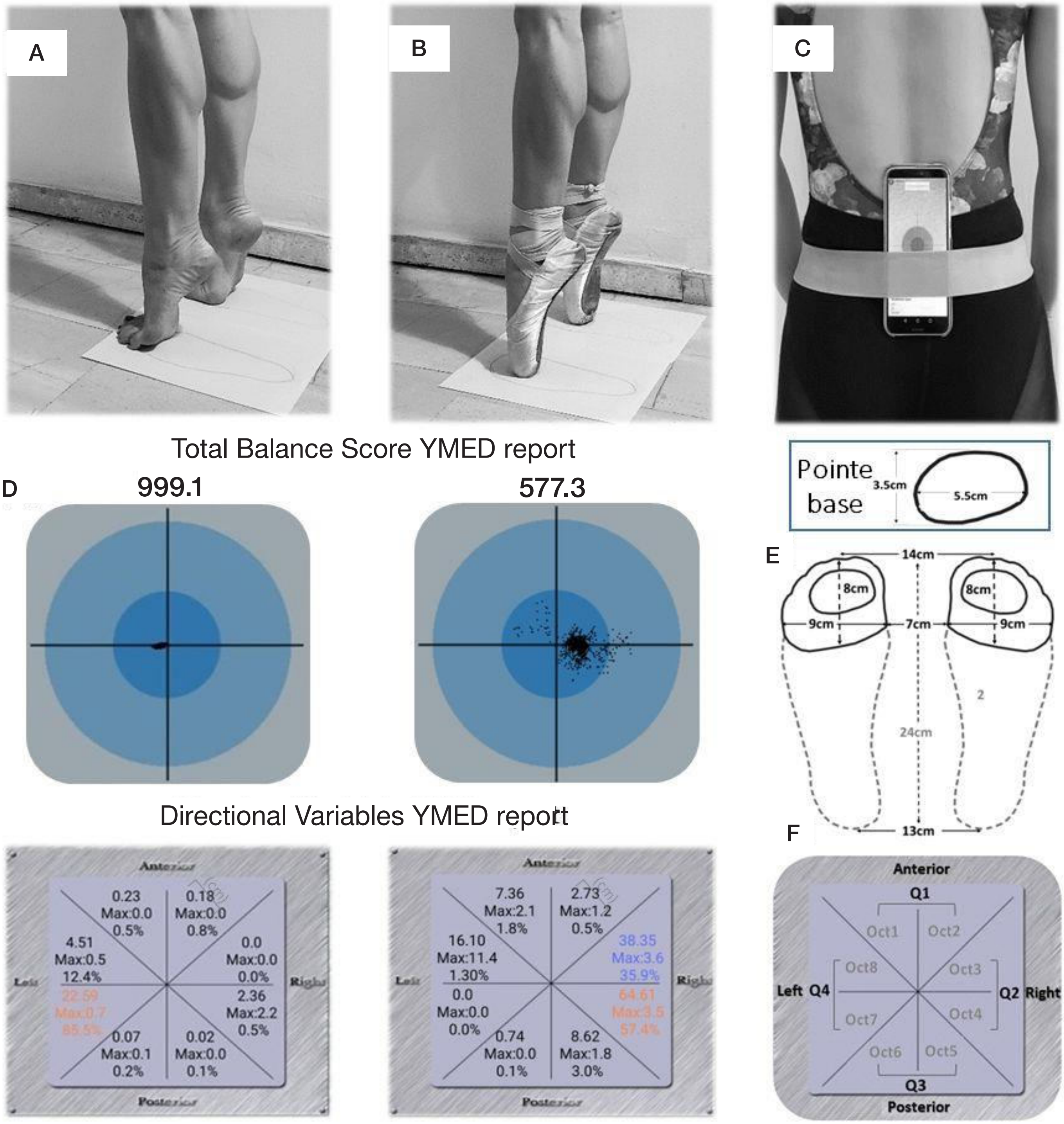


Figure. 1. Illustration of the unshod (A) and the en pointe (B) relevé stance, as well as the smartphone placement (C) To ensure the same feet repositioning in all trials, a piece of paper secured on the floor surface was used to outline the base of support. Panel D shows extracts of the YMED Balance Test reports saved in the smartphone for the total balance score (1 decimal point resolution), as well as for the directional variables of the sum (cm), the maximum (cm) (2 decimal points resolution), and the time percentage (% ttotal, decimal point resolution, 100% = 10-second data collection duration). Red font indicates the octadrant where the peak directional values were recorded. Panel E illustrates the base of support outline for a representative participant (to facilitate visualization, the dotted lines indicate the full floor contact). Panel F presents the original directional octadrants (Oct) in which the YMED Balance Test provides the spatial and temporal directional variables of the centre of mass point displacement, and the directional quartiles (Q) used to facilitate the conceptualization of the centre of mass orientation results.

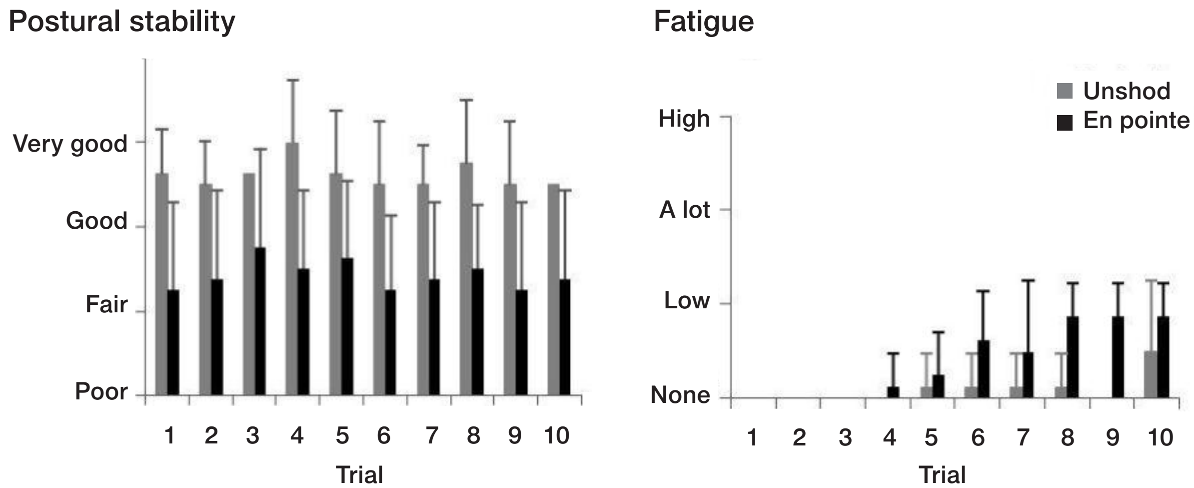


Figure 2. Participants' responses to the 4-point Likert scale concerning postural stability and perceived fatigue immediately after each trial of the unshod (grey bars) and the en pointe (black bars) relevé conditions

with the floor until instructed to adopt the relevé position. After adopting the relevé position (Figure 1A, B), a vocal cue informed them to slowly release the bar and relax their arms at the side of their body just before the calibration initiation (a vocal instruction was provided for gaze fixation on a target in front of them, at eye level). The mobile phone was securely positioned (narrow elastic ring band) on the dorsal body surface at the O5 level (i.e., approximating the CoM position) (Figure 1C). In both the unshod and the en pointe condition, the perimeter of the initial feet placement (preferred width and orientation) was outlined on a piece of paper secured on the floor, to ensure the same feet repositioning in all trials (Figure 1E).

After each one of the trials, all participants rated their postural stability and sense of fatigue using a 4-point Likert scale. The ratings (Figure 2) indicated that the postural stability in the en pointe relevé was about 50% lower than in the unshod relevé. Despite an increasing trend after the 6th trial in the en pointe relevé, the fatigue ratings did not exceed the low level. Overall, the Likert scale ratings allow the inference of no learning or fatigue effect along with the 10 trials in both the unshod and the en pointe relevé. The presence of a learning and/or fatigue effect was further examined through statistical procedures; these are described in the statistics section and their outcomes are presented in the results section.

Variables

The YMED Balance Test provides a total postural stability estimation (total balance score with 1 decimal point resolution) ranging from 0 to 1000 (0: worst balance, 1000: best balance). The YMED Balance Test (personal communication with the developer) estimates the total balance score from the CoM point displacement within 10 concentric circular zones, with zero CoM position defining the centre of the concentric circular zones, and the inner and outer zone indicating the better and the worse stability, respectively. It also provides spatial and temporal data for the CoM point orientation within octadrant zones, that is, the sum of the CoM point displacements (cm, 2 decimal points resolution), the maximum CoM point displacement (cm, 2 decimal points resolution), and the time percentage of the CoM point displacement (% ttotal, 10 s = 100%, 1 decimal point resolution), in each of the 8 octadrants. The 10-trial average consisted of the value of the balance score, as well as of the octadrant spatial and temporal values of the CoM point displacement. For conceptual facilitation of the CoM orientation, the octadrant values (Oct1, Oct2, Oct3, Oct4, Oct5, Oct6, Oct7, Oct8) were summed into quartile values indicating the anterior (Q1 = Oct1 + Oct2), rightwards (Q2 = Oct3 + Oct4), posterior (Q3 = Oct5 + Oct6), and leftwards (Q4 = Oct7 + Oct8) CoM point displacement (Figure 1F).

Statistical analysis

The statistical analysis included paired *t*-tests between the unshod and the en pointe relevé conditions, with the 10-trial average constituting the individual value (respectively for each of the examined variables) inserted in the statistical analysis. Data normality was not tested as with less than 30 cases such a test is not actually of usefulness, and a similar or even lower number of cases is not uncommon in other relevant studies (n = 15 [7], n = 10 [21], n = 10 [22], n = 5 [23]). However, we applied the Spearman-Brown prophecy formula [24] to estimate the number of measurements (k) necessary to achieve the desired level of optimal reliability (R_k):

$$k = [R_k*(1 - R)] / [R*(1 - R_k)]$$

The application of this formula in our study, with the desired level of reliability (R_k) set at 0.70, 0.80 and with R being the value of the intraclass correlation coefficient (ICC) for the reliability between the 1st and 2nd trial (R = 0.20 and R = 0.80 for the unshod and the en pointe, respectively), led to confirming the use of at least 9 trials in the unshod and just 2 trials in the en pointe relevé in this respect. As we aimed at a balanced design, we finally chose 10 trials for both relevé conditions.

Relative and absolute reliability measures were applied separately in the unshod and the en pointe relevé conditions. There are several forms of the ICC [25], but considering that the reliability that is in question concerns absolute agreement, the 2-way random effects absolute agreement method, also known as ICC(2,1), was the most appropriate for the present study [21]. The ICC's upper and lower bounds of their 95% confidence interval were also extracted. Relative reliability was classified in accordance with Fleiss [26] (ICC > 0.75: excellent, ICC between 0.40 and 0.75: fair to good, ICC < 0.40: poor). Absolute reliability was estimated by using the standard error of measurement (SEM) and the percentage SEM (SEM%). SEM accounts for the within-subject variability, assesses how precisely a test measures a subject's true value, has the same units as the measure of interest, and is not sensitive to the between-subject variability of the data. Thus SEM, indicates the expected variation in observed values that occurs owing to the measurement error (if reliability = 0, SEM will equal the standard deviation of the observed values; if test reliability = 1.00, SEM will be zero). SEM was estimated as the square root of the mean square error term from ANOVA, as this estimation has the advantage of being independent of the specific ICC and allows more consistency in interpreting SEM values from different studies [27]. Furthermore, SEM% allows a comparison of the expected variation in observed values between different conditions (as the 2 relevé conditions of the present study) and was defined as (SEM/$\bar{x}$) × 100, where $\bar{x}$ is the average of all observed values. Following the suggestion by Hopkins [28], the potential learning or fatigue effects on ICC and SEM were examined with separate analyses of accumulated trials (1st to 2nd, 1st to 3rd, ..., 1st to 10th), as well as of consecutive pairs of trials (1st vs. 2nd, 2nd vs. 3rd, ..., 9th vs. 10th). Also, in each relevé condition, we tested the trial effect (total of 10 trials) via repeated measures analysis, separately for each variable. If the Mauchly's test indicated a violation of data sphericity (p < 0.05), the Greenhouse-Geisser correction was used to estimate the trial effect significance. All statistical analyses were carried out with the IBM SPSS software v. 26.0, with the level of significance set at α = 0.05.

Ethical approval

The research related to human use has complied with all the relevant national regulations and institutional policies, has followed the tenets of the Declaration of Helsinki, and has been approved by the School of Physical Education and Sport Science, National and Kapodistrian University of Athens, Greece (approval protocol number: 1165/12-02-2020).

Informed consent

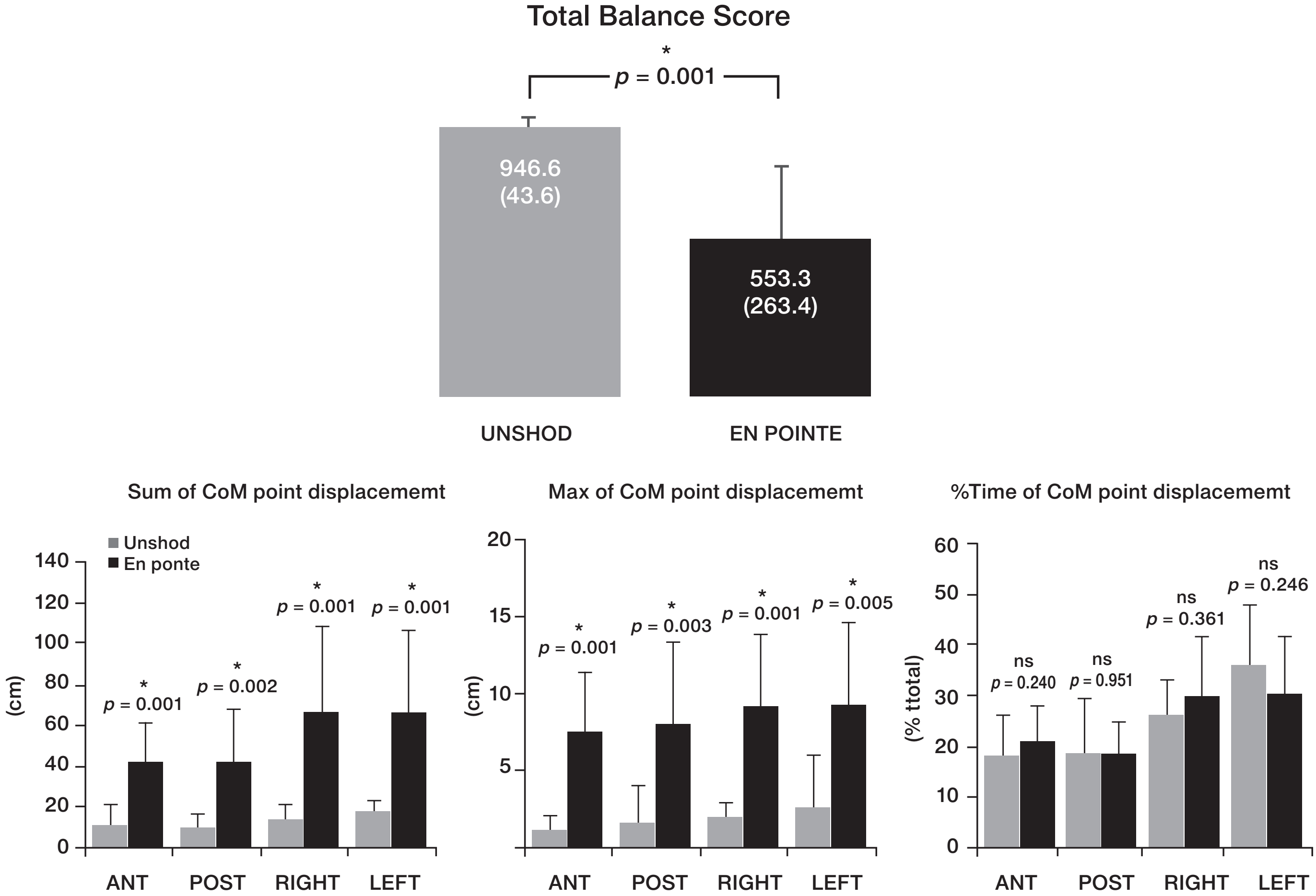
Informed consent has been obtained from all individuals included in this study.

Results

Comparison between unshod and en pointe relevé

Figure 3 presents the mean of accumulated trials, as well as its lower and upper bound of the 95% confidence intervals, for the total balance score and the spatial and temporal directional variables, for the total of 10 trials for testing the trial effect via repeated measures analysis, separately for each variable. No significant trial effect was found, either for the total balance score or for any of the spatial and temporal directional variables (p > 0.05).

The total balance score was 946.6 ± 43.59 in the unshod relevé, with a significantly lower value in the en pointe condition (553.3 ± 263.4) (t = 5.053, df = 12, p < 0.001) (Figure 2). All spatial quartile measures were also significantly lower in the en pointe condition (p < 0.05), with no significant difference (p > 0.05) concerning the temporal measures (time percentage of the CoM displacement) (Figure 2).



CoM – centre of mass, ttotal – total time, ns – non-significant difference at $p < 0.05$
ANT – anteriorly, POST – posteriorly, RIGHT – rightwards, LEFT – leftwards
* significant difference at $p < 0.05$

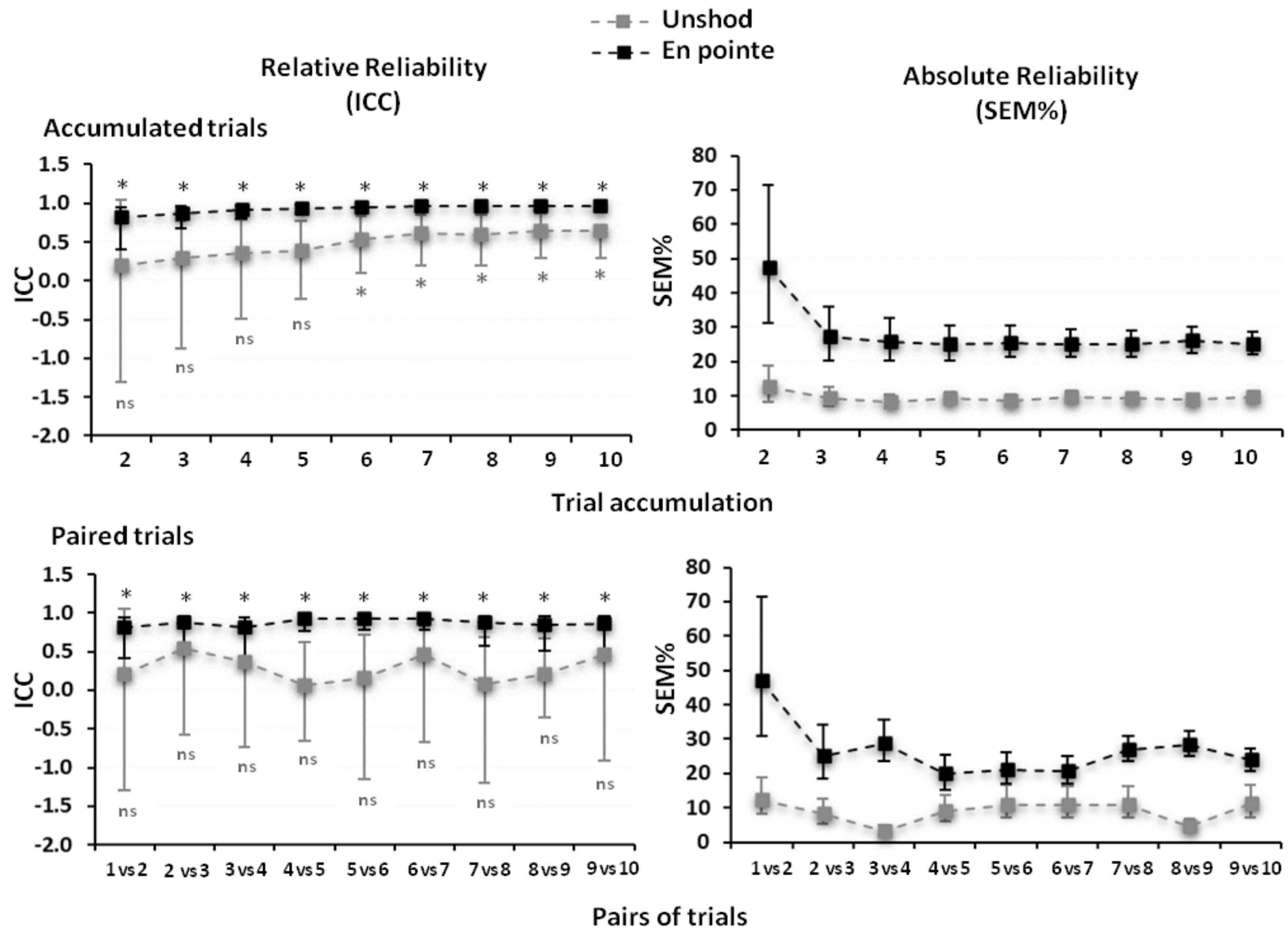
Figure 3. Mean (standard deviation) of the total balance score in the unshod (grey bars) and the en pointe (black bars) condition

Spatial (sum and maximum of the CoM point displacement) and temporal (time percentage of the CoM point displacement) per quartile direction. The significance (*p* value) of the difference between the unshod and the en pointe conditions is noted. There was no significant difference between anterior and posterior direction (unshod relevé: $p = 0.211$, 0.380, 0.947; en pointe relevé: $p = 0.977$, 0.712, 0.519 for the sum, maximum and time percentage (% ttotal) of the CoM point displacement, respectively). Concerning the rightwards vs. leftwards comparison, no significant difference was found for the spatial measures (unshod relevé: $p = 0.997$, 0.712; en pointe relevé: $p = 0.946$, 0.796 for the sum and maximum of the CoM point displacement, respectively). However, the leftwards % ttotal was significantly greater compared with rightwards in the unshod relevé ($p = 0.037$), with no significant difference in the en pointe condition ($p = 0.937$) (paired *t*-tests, separately for each variable, were applied for all bi-directional comparisons)

Relative – absolute reliability

Total balance score

The reliability indices imply a consistently lower relative and a consistently higher absolute reliability of the total balance score in the unshod compared with the en pointe condition, both in the accumulated and paired trials (Figure 4). The trial accumulation indicates a minimum of 6 trials in the unshod relevé and just 2 trials in the en pointe relevé for significant relative reliability. The paired trials reliability was not significant in the unshod condition, whereas all consecutive pairs indicated significant reliability in the en pointe condition. The absolute reliability points at an about triple SEM% in the en pointe compared with the unshod relevé consistently for all trial accumulations except the first 2 ones. The mean ± standard deviation of total balance score SEM% equalled, in the unshod and the en pointe relevé, respectively, 9.5 ± 1.2%



ICC – intraclass correlation coefficient, SEM% – percentage standard error of measurement, ns – non-significant ICC
* significant ICC

Figure 4. Relative (ICC) and absolute (SEM%) total balance score for the accumulated and paired trials in the unshod (grey markers) and the en pointe (black markers) conditions. The error bars indicate the lower and upper bound of the 95% confidence intervals

and 27.9 ± 7.2% for overall accumulated trials and 9.0. ± 3.2% and 26.9 ± 8.3% for overall paired trials (Figure 4).

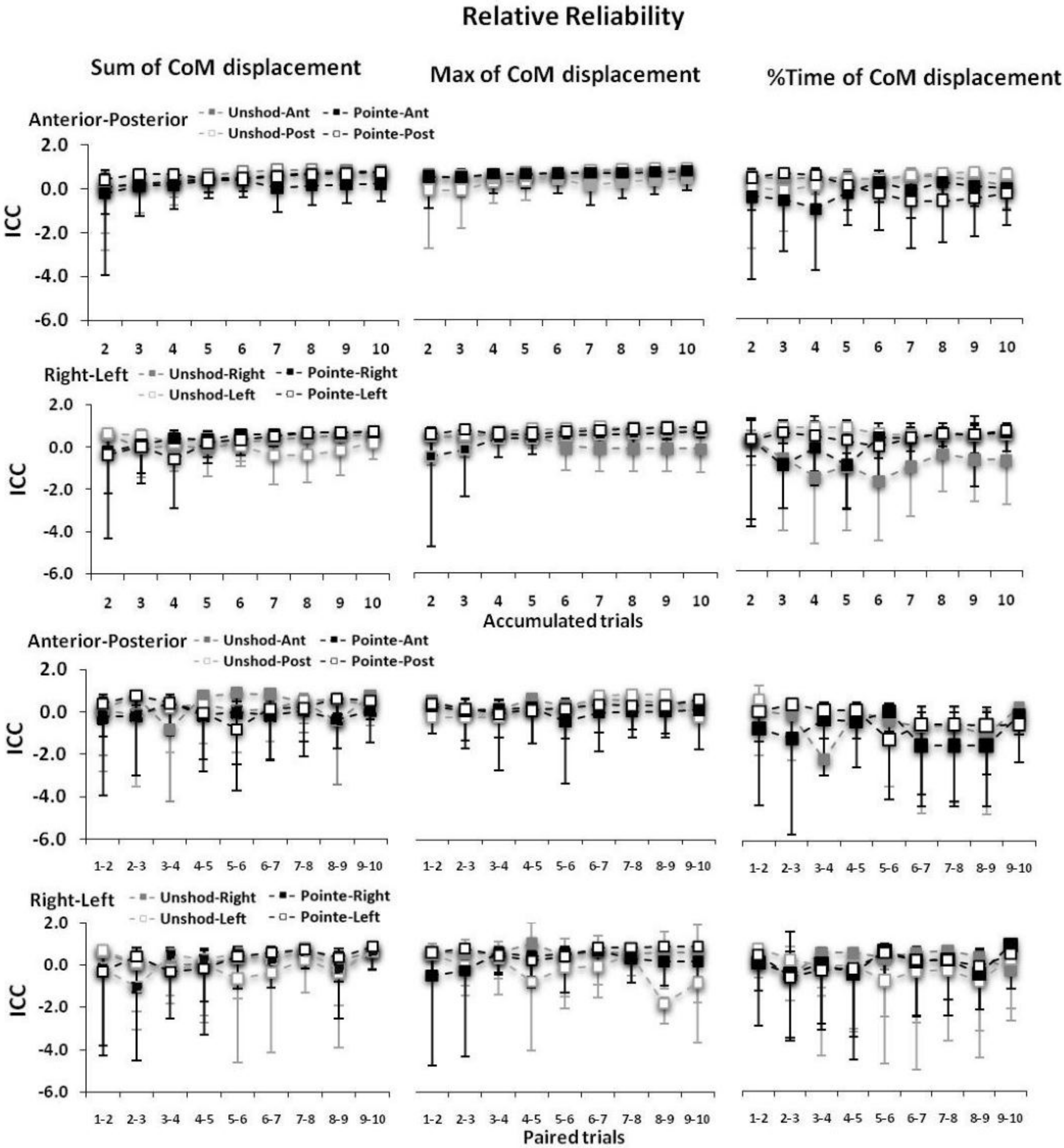
Directional variables

The directional variables demonstrated cases of significant fair to good reliability for the sum of the CoM displacement, and excellent reliability for the maximum of CoM displacement (in the accumulated and paired trials), whereas the time percentage of the CoM displacement presented overall non-significant reliability. However, no consistent pattern of significant reliability was demonstrated either for trial accumulation or for pairs of trials (Table 1, Figure 5). The absolute reliability of the directional variables (Figure 6) indicates a decrease and a stabilization of SEM% after a 6-trial accumulation; however, the SEM% of the directional variables is rather too high in both the unshod and the en pointe relevé (mean ± standard deviation of SEM% across all 4 directions for the sum, the maximum, and the time percentage of the CoM point displacement, respectively: overall for accumulated trials: 114.1 ± 20.6%, 105.5 ± 35.8%, and 109.4 ± 15.1%; overall for paired trials: 106.1 ± 25.3%, 96.5 ± 35.9%, and 115.7 ± 29.2%).

Discussion

The purpose of this study was to evaluate the reliability of assessing ballet dancers' postural stability in the unshod and the en pointe relevé position with a smartphone application.

As expected, postural stability was significantly lower (by about 48%) in the en pointe compared with the unshod relevé position. Similarly, all CoM spatial



CoM – centre of mass, ICC – intraclass correlation coefficient,
Ant – anteriorly, Post – posteriorly, Right – rightwards, Left – leftwards

Figure 5. Relative reliability (ICC) of the directional variables for the accumulated and paired trials in the unshod (grey markers) and the en pointe (black markers) relevé conditions. The error bars indicate the lower and upper bound of the 95% confidence intervals. The significance of ICCs is presented in Table 1

Table 1. Relative reliability significance ($p < 0.05$) for the directional variables presented in Figure 5

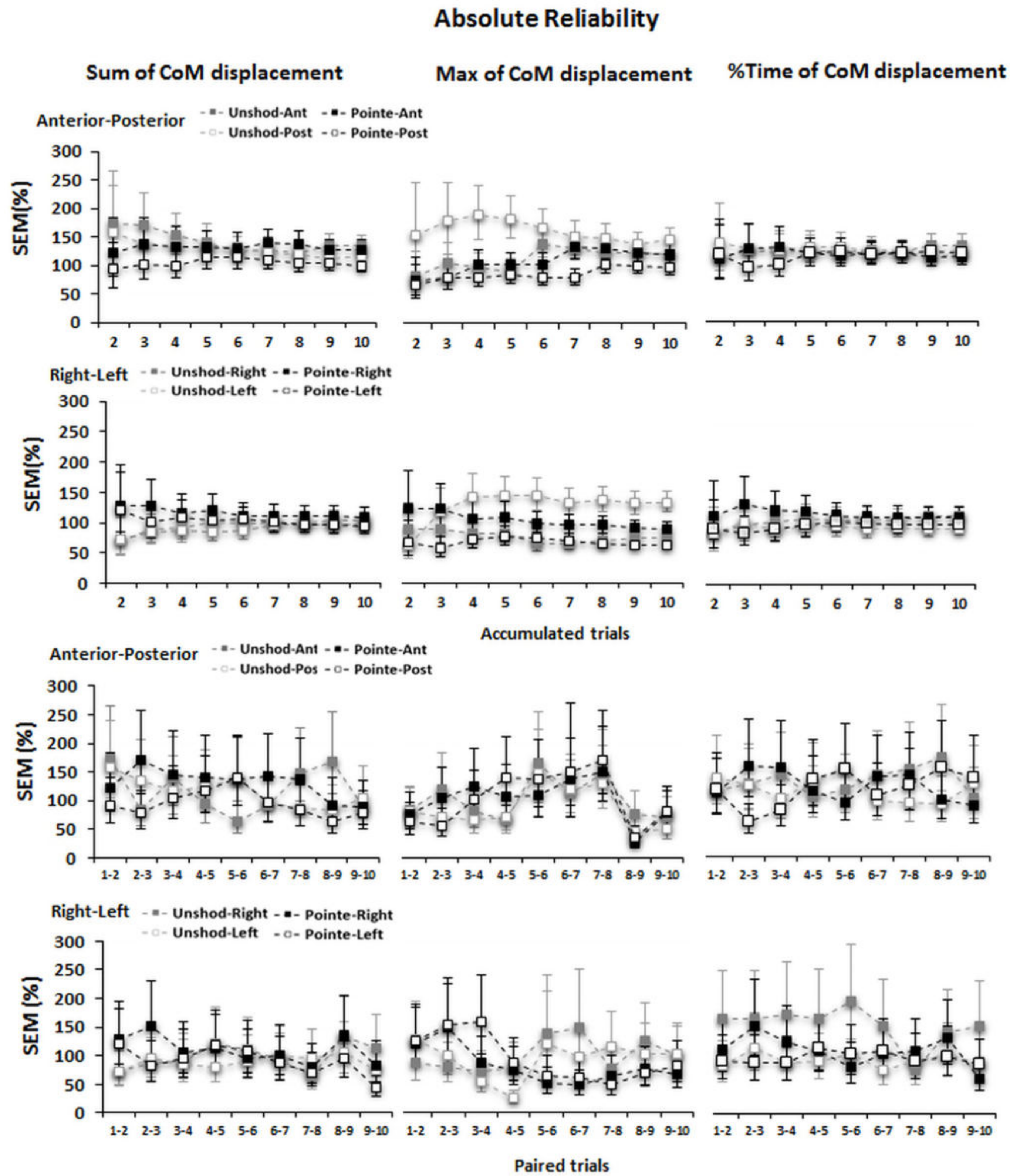
	Sum of CoM displacement								Max of CoM displacement								%Time of CoM displacement							
	Unshod		En pointe		Unshod		En pointe		Unshod		En pointe		Unshod		En pointe		Unshod		En pointe		Unshod		En pointe	
	A	P	A	P	R	L	R	L	A	P	A	P	R	L	R	L	A	P	A	P	R	L	R	L
Accumulated trials																								
2	ns	ns	ns	ns	ns	*	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
3	ns	ns	ns	*	ns	*	ns	ns	ns	ns	*	ns	ns	ns	ns	**	ns	ns	ns	*	ns	ns	ns	ns
4	ns	ns	ns	*	ns	ns	ns	ns	*	ns	ns	*	*	*	ns	*	ns	ns	ns	*	ns	*	ns	ns
5	*	ns	ns	*	ns	ns	ns	ns	*	ns	*	*	ns	**	ns	*	ns	ns	ns	ns	ns	*	ns	ns
6	**	*	ns	*	ns	ns	*	ns	*	*	ns	*	ns	**	*	*	ns	ns	ns	ns	ns	ns	ns	ns
7	**	*	ns	*	ns	ns	*	*	**	**	ns	*	ns	**	*	**	*	*	ns	ns	ns	ns	ns	ns
8	**	*	ns	*	*	ns	*	*	**	**	ns	*	ns	**	*	**	*	*	ns	ns	ns	ns	ns	ns
9	**	*	ns	*	*	ns	*	*	**	**	ns	*	ns	**	*	**	ns	*	ns	ns	ns	ns	ns	ns
10	**	*	ns	*	*	ns	*	**	**	**	*	**	ns	**	*	**	ns	*	ns	ns	ns	ns	ns	ns
Paired trials																								
1–2	ns	ns	ns	ns	ns	*	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns
2–3	**	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	ns	**	ns	ns	ns	ns
3–4	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
4–5	**	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
5–6	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
6–7	**	ns	ns	ns	ns	ns	ns	ns	**	**	ns	ns	ns	ns	*	**	ns	ns	ns	ns	ns	ns	ns	ns
7–8	ns	ns	ns	ns	**	ns	*	*	*	**	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns
8–9	ns	ns	ns	*	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns
9–10	**	ns	ns	ns	ns	*	ns	**	ns	ns	ns	*	ns	ns	ns	**	*	ns	ns	ns	ns	ns	**	ns

CoM – centre of mass, A – anteriorly, P – posteriorly, R – rightwards, L – leftwards, ns – non-significant reliability
* fair to good reliability (0.40 > ICC > 0.75), ** excellent reliability (ICC > 0.75) (intraclass correlation coefficient [ICC] classification in accordance with Fleiss [26])

measures indicated significantly lower postural stability in the en pointe compared with the unshod condition, whereas the directional temporal distribution of the CoM point displacement did not differ between conditions. Overall, taken an adequate number of trials, the results encourage the use of a smartphone application for testing standing postural stability in ballet dancers. This approach employs a low-cost and of high-portability tool for field assessment compared with expensive and of limited-portability laboratory equipment such as the force plate gold standard [2, 7, 26], accelerometers [3, 7, 10–12], or a motion capture system [6, 8, 9].

The results indicate the total balance score as the most reliable postural stability measure provided by the YMED Balance Test application used in the present study, whereas the directional CoM information (spatial or temporal) appears of relative but not of absolute reliability value. The superior reliability of the total balance score over the directional CoM measures is supported by both the relative and absolute reliability indices and agrees with studies of varying smartphone reliability depending on the variable used to examine postural stability [16]. Overall, the total balance score reliability appears similar to other smartphone applications; Amick et al. [14] report excellent relative reliability with ICCs of 0.78 (SEM: 5.82) in standing tasks (full contact with the floor, double or single leg standing, 2 trials) using the Sway balance mobile application. Good to excellent relative reliability ICC indices are also reported for postural stability assessments with accelerometers (ICC: 0.62–0.71 [10], ICC: 0.736–0.972 [12]).

The reliability criteria themselves warrant careful computation and interpretation owing to the variety of computational models and the wide range of classification boundaries [25, 26]. Furthermore, one should realize the different interpretations of relative (the degree to which individuals maintain their position in a sample over repeated measurements) vs. absolute (the degree to which repeated measurements vary for individuals) reliability indices [26]. Specifically, the ICC indices in our study indicate good relative reliability for the total balance score in the unshod condition and excellent relative reliability in the en pointe condition. Nevertheless, as may be inferred from its



CoM – centre of mass, SEM% – percentage standard error of measurement,
Ant – anteriorly, Post – posteriorly, Right – rightwards, Left – leftwards

Figure 6. Absolute reliability (SEM%) of the directional variables for the accumulated and paired trials in the unshod (grey markers) and the en pointe (black markers) relevé conditions. The error bars indicate the lower and upper bound of the 95% confidence intervals

about 1/3 lower SEM%, the absolute reliability of the total balance score is better in the unshod than the en pointe condition. Also, the degree of reliability of the spatial measures is not consistent in the unshod vs. the en pointe condition, indicating a directional inter-condition differentiation for the sum, but not for the maximum of the CoM point displacement. Precisely, in the unshod condition, the relative reliability was fair to good in the anterior and posterior directions but poor in the medial and lateral ones, while the opposite was found for the en pointe condition. Concerning the maximum of the CoM point displacement, in both the unshod and the en pointe conditions, the relative reliability appears consistently higher (good to excellent or fair to good) in the medial and lateral directions compared with the anterior and posterior ones. Nevertheless, despite the existence of good or excellent relative reliability for the spatial directional variables, their high SEM% indicates that the directional absolute reliability of the YMED Balance Test is poor.

One may argue that a methodological bias may underlie the directional reliability differences, as well as the greater leftward rather than rightward spatial and temporal measures. Bias in research is an important issue; as it may not be totally eliminated, it is important to understand it in order to consider strategies to minimize it. However, an accelerometer sensor bias or an environmental attractor (i.e. the examiner's position or a wall nearby) are not likely to explain the directional differences observed in the present study. Before the initiation of the measurements, the accelerometer sensor of the smartphone was calibrated and the procedures described by Ma et al. [20] were applied for static bias testing. Furthermore, the examiner was standing behind and not laterally to the participant to monitor the smartphone's screen, and although a wall existed nearby, it was not consistently on the right or left side of the participants. The stance leg dominance could possibly associate with the directional difference (the left leg was reported as the preferred stance leg for work en pointe and also the left leg was indicated as the stance dominant one in the leg dominance test). Indeed, leg dominance appears to differentiate the asymmetrical function of the feet (by how one foot performs the mobilizing function, emphasizing the precision of the movement, whereas the other foot stabilizes the upper body, providing support for the tracing foot) [29]. However, leg dominance does not appear to influence postural stability during the quiet upright stance or the single-legged stance [29].

Force plates are considered the gold standard for postural stability evaluation and allow a high test-retest reliability, but they are generally expensive and inaccessible for field testing [11, 15, 16]. In turn, accelerometers demonstrate reliability indices that are comparable with those allowed by force plates [11]. Indeed, it is not of surprise that some researchers suggest accelerometers as superior to force plates owing to their ability to quantify human movement in natural environments [11]. Thus, because of their built-in accelerometers, smartphone applications may provide a valid alternative to the force plate gold standard for a field setting evaluation of postural stability [9, 11, 14, 16, 17]. Nevertheless, the reliability of measurements acquired with smartphone applications remains an issue of concern [9, 14, 16, 17].

The mobile phone was positioned at the lumbar level (CoM approximation) in accordance with the YMED Balance Test guidelines, coinciding with the majority of research using accelerometers to assess postural stability [11, 22]. It must be noted, though, that other body placements are also applied in smartphone application studies (i.e. thorax, knee, ankle), with the degree of reliability varying not only owing to placement but also in conjunction with the type of standing test [9, 13, 18]. For instance, depending on the type of balance test (static or dynamic), reliability might be higher in the thoracic than the lumbar level [9]. Similarly, depending on the degree of test difficulty, the ankle location may provide a greater detection sensitivity, easiness of application, and feasibility, but this would be at the cost of potentially greater asymmetry between the left and right legs [18]. Shah et al. [18] attribute the lower reliability of the trunk placement to the low sampling rate of their smartphone built-in accelerometer (i.e. 14–15 Hz). They associate the low sampling rate with a potential failure of trunk movement detection if the individual's balance is not significantly challenged. Thus, the sampling rate should be taken into consideration when comparing results with other studies, particularly when research-grade accelerometers are used, which allow a sampling rate of up to 1000 samples per second [22]. However, as mobile phone technology advances and the embedded accelerometers improve, they may be able to provide higher sampling rates and more robust measures of standing balance. Indeed, the main limitation of the present study is that the measurements of the smartphone application were not compared with a gold standard such as a force plate or a research-grade accelerometer tested for validity and reliability.

The number of trials necessary to obtain a good reliability index is a concern in many studies [14, 21], even for the most reliable among assessment tools, i.e. the force plate gold standard, where just 2 or 3 trials may ensure excellent relative reliability [21]. Just 2 trials are also reported to provide excellent intersession relative reliability when using a smartphone application to evaluate postural stability in the typical bipedal stance [14]. However, the relevé position, and particularly the en pointe one, is not among the stances commonly examined in previous studies concerning ballet dancers' postural stability [1–5]. Thus, a total of 10 trials were selected to ensure that the number of trials would be adequate to extract safe reliability conclusions for both the unshod and the en pointe relevé stances.

As emphasized by Atkinson and Nevill [30], the higher the SEM%, the lower the absolute reliability and the lower the precision of the obtained results. However, to the best of our knowledge, there do not appear specific criteria concerning SEM% classification. SEM% of 9–14% was classified by Jaworski et al. [10] as very good reliability, while values of 40% were interpreted as significantly worse (single-legged standing, inertial sensor accelerometer). Similarly, Pooranawatthanakul and Siriphorn [9] report SEM% at about 16% for common standing balance tests performed with a mobile phone application. Taken into account these 2 studies, we may infer very good absolute reliability of the total balance score in the unshod condition and moderate absolute reliability in the en pointe condition, with the latter most likely within a normal range owing to its extreme anatomical and mechanical configuration. Nevertheless, future studies are necessary to provide normative data concerning the reliability of assessing postural stability during the en pointe relevé position, which is not among the standing positions commonly examined in the existing literature.

Conclusions

Postural stability was significantly lower (by about 48%) in the en pointe compared with the unshod relevé position. The total balance score is highlighted of good and excellent relative reliability in the unshod relevé, as well as of good and moderate absolute reliability in the en pointe relevé. The directional parameters of the CoM point displacement demonstrate an overall good relative reliability but their absolute reliability is rather poor. Overall, a minimum of 8 trials are suggested for reliable results in both the unshod and the en pointe relevé. The results encourage the use of a smartphone application for testing standing postural stability in ballet dancers as it constitutes a low-cost and high-portability tool for field assessment.

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Conflict of interest

The authors state no conflict of interest.

Author contributions

All authors participated in the research concept and design, the collection and/or assembly of data, the data analysis and interpretation, as well as in writing, critical revision, and final approval of the article.

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COMPARING THE KINEMATICS OF BACK SQUATS PERFORMED WITH DIFFERENT HEEL ELEVATIONS

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ABSTRACT
Purpose. Back squat (BS) is a popular exercise owing to its capacity to develop lower limb strength. During BS, trunk inclination and knee range of motion (RoM) are relevant aspects of a proper technique, and these movement kinematics parameters can be positively altered with official weightlifting shoes lifting the heel 13 mm above the ground. Wedges are a low-cost alternative to lifting the heel to different heights, but movement kinematics adaptations with higher elevations, above 25 mm, are not well described in the literature. Thus, we compared the effect of different heights of heel wedges on BS kinematics.
Methods. Fifteen experienced recreational weightlifters (22 ± 5.4 years; 83 ± 11 kg; 179 ± 6 cm; 5 ± 2.1 years of BS experience) were conveniently selected. Three randomized conditions were applied: barefoot (B), 25-mm (W25), and 50-mm wedges (W50). BS movement was assessed by kinematic analysis with an optoelectronic camera system.
Results. After ANOVA, the post-hoc indicated significant RoM differences in reducing trunk ($F = 27.27$; $p < 0.01$) and increasing knee ($F = 16.87$; $p < 0.01$) flexions between conditions. Post-hoc analysis verified decreasing trunk inclination (B > W25 > W50; $p < 0.05$) and increasing knee (B < W25 < W50; $p < 0.05$) RoM with increasing wedge height.
Conclusions. Higher wedges allowed positive adaptations by promoting a more upright trunk position and greater BS depth. Using a heel wedge can be a low-cost and viable strategy to optimize BS technique in a variety of training settings and contexts.
Key words: resistance training, range of motion, injury prevention, biomechanics, wedge

Introduction

Back squat is a major exercise used in resistance training [1] and several sports modalities. An organized and systematic practice of back squat may promote lower limb strength and power gains [2], hypertrophy [3], assistance in rehabilitation processes [4], and maintenance of elderly strength and functionality [5]. Given the enhanced applicability of this exercise, performing it properly is essential for different goals and sports. Within this context, range of motion (RoM) is an aspect of performance that needs to be cautiously considered during back squats. Besides being proportionally related to different gluteus maximus activation [6] during back squat, higher RoMs on key joints (e.g. knee) also promote better adaptations in resistance training programs mainly owing to increased time under tension: a significant variable that aids muscle gains [7]. Recent experimental evidence showed that performing a full squat is superior to half squat training regarding gluteus maximus and adductor hypertrophy [3]. Another issue that deserves attention in back squat kinematics is the lower limb and lumbar spine joints overload. For instance, these areas are related to increased injury risk during a back squat, especially when performing with inappropriate form or heavy loads [8–10]. This increases muscle torque and shear forces on the lumbar spine, which interact better with compressive forces that shear [1]. Therefore, proper movement technique is crucial.

Previous research has shown that adequate technique is related to the distance between feet, appropri-

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ated shoes wearing, and vertical trunk position (to mention a few) [1], since these points decrease shear forces at lower limbs and lumbar spine [1]. To improve some of these aspects, it has been documented that using proper weightlifting shoes while back squatting can increase knee RoM [11]. Weightlifting shoes are designed with a 13-mm elevation between the forefoot and the heel; this parameter has been defined by the International Weightlifting Federation and the value is sufficient to promote a more vertical trunk position, greater RoM in the knee joint, and better stability during back squat [12, 13]. While these investigations suggest technical positive adaptations with weightlifting shoes, more recent research has been unable to verify benefits of squatting with raised heel, since similar kinematics were observed when participants squatted barefoot [14, 15]. Additionally, general practitioners include other training methods on regular routines, like post-activation potential, being more practical with using running shoes than weightlifting shoes. Hence, an alternative approach to lifting the heel during this exercise can be an adapted wedge without a standard height, such as iron plates or a squared wooden block. With this approach, it would be possible to evaluate the effects of squatting with the heel elevated above the 13-mm height provided by weightlifting shoes. For instance, Charlton et al. [16] described positive outcomes (e.g. less trunk flexion) with a 25-mm wooden block beneath the heel during back squat in trained male subjects. In turn, Lee et al. [14] did not verify modifications in the knee, thoracic, or lumbar joint kinematics when comparing back squat performed barefoot vs. with 33-mm elevated heels. It is important to highlight that Lee et al. [14] investigated recreational weightlifters, while Charlton et al. [16] assessed trained participants. Considering that most skilled participants present a gold standard technique [17], investigating this population is a way to attribute kinematic differences by using wedges.

In the previous evidence, the literature remains inconclusive regarding the benefits of squatting with the heel elevated above 25 mm, and no investigation up to date has analysed the modifications of back squat kinematics using wedges higher than those. Thus, to understand the greater height that promotes positive adaptations, without an uncomfortable heel elevation, can be useful for practitioners to apply wedges in the height range in daily practice. Furthermore, frontal plane analysis of the hip joint (adduction and abduction movements) is lacking in the previous research. Given this scenario, this topic still needs further research to clarify whether lifting the heel while back squatting is an adequate strategy to optimize biomechanical movement parameters. This study aimed to describe the modifications that heel wedges can promote in back squat kinematics. We analysed the kinematics of the lower limb joints (ankle, knee, and hip) and trunk motion in 3 back squat conditions: barefoot (B), 25-mm wedge (W25), and 50-mm wedge (W50). We set 50 mm as this was the height limit to lift the heel with comfort. Considering previous evidence of load influence in knee and hip kinematics during back squat [18], and that load may promote fatigue (which is a potentially confounding effect in our results), it was decided that the back squat would be implemented without load in this study. Thus, our study aimed to assess maximal RoM without external interferences and with minimal variation of technique across trials. We hypothesized that a higher heel elevation would (H1) decrease anterior trunk inclination and (H2) increase knee and ankle RoM. The results can contribute to better understanding the influence of an elevated heel during back squat kinematics, aiding an adequate prescription that can be considered in different contexts by coaches, athletes, resistance training professionals, and practitioners.

Material and methods

Participants

The sample size was calculated by G*Power 3.1 (Franz Faul, Germany) for a repeated-measures ANOVA within factors (1 group × 3 measures), considering a moderate effect size according to Cohen (d = 0.5), α error probability = 0.05, and power (1 – β) = 0.8, following the recommendations by Faul et al. [19]. On the basis of these parameters, a minimum of 9 subjects was estimated.

A total of 15 men, resistance-trained adults (22 ± 5.4 years of age, 83 ± 11 kg, 179 ± 6 cm), were conveniently selected for this study. They had been injury-free in the lower limbs and trunk for at least 6 months before the research. All subjects had a minimum experience with back squat exercise of 3 years (5 ± 2.1 years on average), performing it at least once a week in their training routine.

Procedures

The participants performed the exercise shirtless, barefoot, and with standardized shorts. We positioned a wooden block below the participants' heel (on calcaneus) to provide the elevations during both experi-

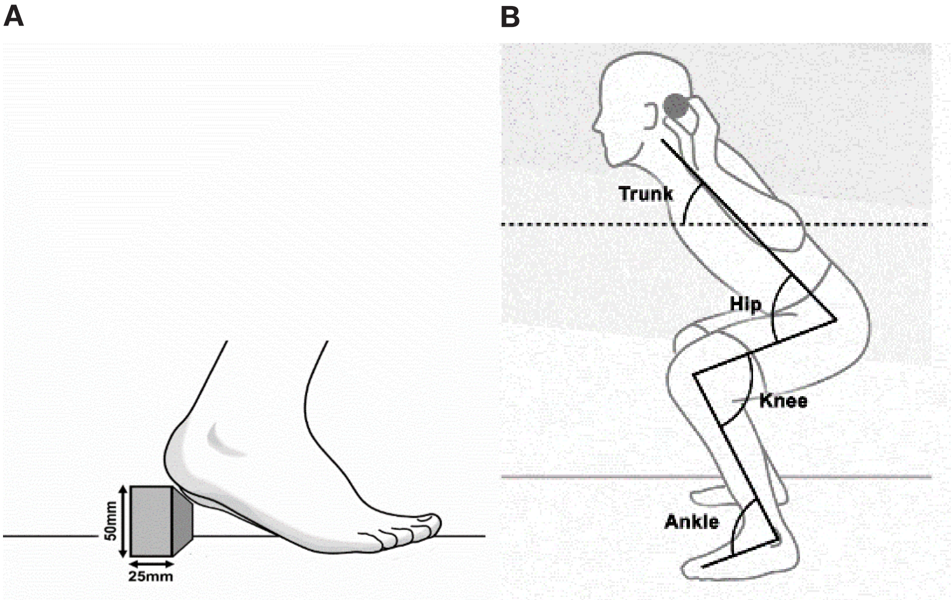

Figure 1. Wooden block representation (A) and sagittal plane angle interpretations (B)

mental conditions (W25 and W50), as represented in Figure 1A. For this study, we made 2 wooden blocks that presented the same measures to support calcaneus between the different heights. For kinematic analyses, reflective markers were positioned on the subject's skin, and the camera manufacturer's calibration procedure was followed. Next, a warm-up set (10 repetitions) in each experimental condition (B, W25, and W50) was performed, followed by rate of perceived exertion scale answer to ensure that the participants were not fatigued. This procedure was in line with the literature recommendations of Borg scale, and all subjects had previous experience with the scale. On resting 2 minutes after the warm-up, the participants performed 3 sets of 6 repetitions in each experimental condition (B, W25, and W50), and rate of perceived exertion scale was measured after each series. The subjects were instructed to perform the back squat with full RoM in all conditions. Another 2-minute sitting interval between sets was allowed. A light wooden stick (Figure 1B) was used to replace the iron bar during the back squat to simulate movement kinematics without additional overload. The condition orders were randomized among the subjects, and a researcher was responsible for replacing the wedge when necessary. Movement speed was controlled by a digital metronome (2 seconds eccentric, 1 second concentric), and the first warm-up series served as a familiarization protocol for the metronome tempo. A black dot fixed at the eye level was positioned on the wall (2 m away) to standardize the visual focus.

Motion analysis

Movement kinematics were assessed by 7 optoelectronic cameras (MX-T-Series) of the Vicon System (v. 1.8.5, Vicon Motion System, Oxford, UK) with a sampling frequency of 100 Hz. The cameras were positioned in a way that at least 2 of them visualized the reflective markers throughout the movement, avoiding gaps during data collection and ensuring accuracy. A total of 35 reflective markers were positioned in the subject's body, in accordance with the Vicon Plug-in Gait Full Body model. The following variables were analysed: maximum, minimum, and RoM of relative angles of hip flexion and abduction, knee flexion, and dorsiflexion, as well as maximum, minimum, and RoM of absolute angles of trunk inclination. Angles in the sagittal plane were interpreted as presented in Figure 1B. The hip abduction angle was interpreted with 180° in the anatomic position, with decreasing angles during abduction and increasing angles during adduction. The right body side was analysed.

All variables (minimum, maximum, and RoM) were acquired in each repetition, and then averaged for each set. Finally, the average of the 3 sets in each condition was used for statistical purposes. Repetition beginning was determined when the spatial position of the C7 marker reached a reduction greater than 4 mm from one frame to another (eccentric phase), while repetition ending was determined when the same marker reached the highest spatial value (concentric phase). The deepest point of the squat movement was determined on the basis of the minimum value of the knee flexion angle.

Data processing

Data were processed by using Vicon Nexus (v. 1.8.5, Vicon Motion system, Oxford, UK). The time series of the joint angles were filtered with a low-pass recursive digital Butterworth filter (4^{th} order, a cut-off frequency of 3 Hz). The filtering parameters were determined after spectral and residual analysis of the signal [20]. Filtering and analysis, as well as the calculation of the variables, were executed by a personalized MATLAB routine (2017a, MathWorks, USA).

Statistical analyses

Normality and sphericity were verified by Shapiro-Wilk's and Mauchly's test, respectively. Mean and standard deviation were used to describe the angles and joint RoMs, while repeated-measures ANOVA compared the RoM between the different heel elevations in each joint. Bonferroni's post-hoc test was performed when necessary. Effect sizes were calculated for RoM in a paired measure design (B vs. W50), considering the correlation between both measures [21], and interpreted in accordance with Cohen [22] in light of recommendations by Rhea [23] for trained subjects. All analyses were conducted with the SPSS software (v. 21.0, IBM Statistics), and significance was set at $p < 0.05$.

Ethical approval

The research related to human use has complied with all the relevant national regulations and institutional policies, has followed the tenets of the Declaration of Helsinki, and has been approved by the State University of Londrina Ethics Committee.

Informed consent

Informed consent has been obtained from all individuals included in this study.

Results

The results showed significant differences in the trunk, knee, and ankle RoM between conditions (Table 1). Post-hoc comparisons verified decreased RoM in the absolute trunk inclination with increasing wedge height (B > W25 > W50; $p < 0.05$). RoM in knee flexion increased as the wedges were higher (B < W25 < W50; $p < 0.05$), while for dorsiflexion, RoM was only significantly increased between the W25 and the W50 conditions ($p < 0.05$). When comparing B against W50, effect sizes indicated a strong effect for absolute trunk ($d = 1.97$), knee ($d = 1.23$), and ankle ($d = 4.68$) RoM. No significant differences were verified in the results of hip flexion or adduction.

Discussion

The heel elevation height significantly affected back squat kinematics, decreasing anterior trunk inclination and increasing knee and ankle RoM. Hence, both hypotheses initially raised (H1 and H2) were accepted. As such, elevating the heel at 25 and 50 mm can produce positive adaptations in back squat kinematics,

Table 1. Range of motion, minimum and maximum displacement of joints during back squat with different heel elevations

Parameter	B	W25	W50	*F*	*p*
	RoM / Min–Max (*SD*)	RoM / Min–Max (*SD*)	RoM / Min–Max (*SD*)		
Trunk (°)	32.8 / 176.1–143.2 (7.1 / 5.9–7.8)	28.6 / 176.8–148.1 (7.9 / 6.0–7.8)	25.3 / 177.0–151.8[a,b] (7.5 / 5.9–7.4)	27.27	< 0.001
Hip flexion (°)	98.6 / 170.4–71.8 (13.6 / 6.5–10.7)	97.5 / 170.0–72.5 (13.1 / 7.0–10.11)	95.9 / 170.1–74.1 (11.9 / 6.8–9.6)	2.67	0.107
Hip adduction (°)	19.2 / 172.9–153.7 (7.5 / 3.2–7.7)	19.9 / 173.3–153.4 (6.3 / 2.7–6.9)	19.3 / 172.7–153.4 (5.6 / 2.9–6.3)	1.28	0.165
Knee (°)	115.1 / 175.7–60.6 (17.8 / 5.3–15.9)	121.7 / 174.3–52.6 (15.8 / 6.8–12.5)	126.2 / 173.6–47.4[a,b] (11.6 / 7.6–8.0)	16.87	< 0.001
Ankle (°)	32.3 / 93.1–60.7 (6.5 / 3.6–4.8)	36.7 / 97.9–61.2 (11.4 / 4.0–9.9)	38.2 / 103.0–64.8[b] (11.6 / 4.0–10.4)	6.97	0.009

B – barefoot, W25 – 25-mm wedge, W50 – 50-mm wedge, RoM – range of motion
[a] $p < 0.05$ vs. B, [b] $p < 0.05$ vs. W25

being possibly applied in different training programs with various exercising goals. Our results corroborate previous studies in the literature, allowing to further understand the effect of elevating the heel during back squat execution and providing information on how professionals and practitioners can use it in exercise programs that involve back squatting.

Lumbar joints are among the most injury-prone areas during back squatting, excessive anterior trunk inclination seems to be the leading cause [8, 10]. Therefore, our results reveal that elevating the heel at either 25 or 50 mm can promote positive adaptations in squat kinematics owing to its capacity to induce a more upright trunk position. Equivalent results have also been verified in resistance-trained practitioners who performed back squat with wooden blocks of 25 mm [16] or weightlifting shoes [12, 13]. This adaptation leads to smaller overload in the lumbar region [24] and may potentially improve the technique in novices. By squatting with less anterior trunk inclination, novices are closer to a movement pattern that is observed in experienced practitioners [17]. Indeed, the maintenance of natural lumbar lordosis curvature, achieved by an upright trunk position, is related to lifting higher loads during the back squat, which suggests another positive outcome of squatting with elevated heels. Practical applications of these results may also be found in rehabilitation programs, whereas professionals can utilize this strategy to aid patients with movement restrictions in these joints, reducing load-related stress in the lumbar region and developing specific protocols to reach individualized goals [4].

Some previous research did not reveal adaptations in trunk inclination as described earlier by elevating the heels [14, 15]. We believe, however, that methodological differences between our and their investigations can account for the divergent results. For instance, Lee et al. [14] analysed women, implemented a load of 80% of one-repetition maximum, and did not instruct participants to squat as deep as possible; in turn, Whitting et al. [15] also analysed loaded conditions (50%, 70%, and 90% of one-repetition maximum). Considering that there are significant differences in kinematics between sexes [25] and that loading affects movement kinematics [15] during back squat, we propose that these differences might explain the distinct outcomes between our analyses. More pressingly, the instruction not to squat as deep as possible hinders further comparisons between the experiments, especially when considering the notion of achieving maximal RoMs. It could be speculated that reduced anterior trunk inclination promoted by a heel elevation would only be observable when squatting at a full depth, as half-squats do not require excessive inclination of the trunk to maintain balance and perform the exercise.

Greater knee RoM values during a back squat with elevated heels, on the other hand, seem to be a more consistent finding in the literature [12–14, 16], especially when participants are asked to perform maximal RoM. This result should be highlighted, as larger RoM increases time under tension, which is a key variable in muscle hypertrophy protocols [26]. The increased RoM leads to superior stretching of the muscle fibres recruited for the movement in question, which induces greater muscle activation patterns in resistance training exercise [27]. Thus, larger RoMs enhance 2 important aspects related to strength and hypertrophy training: time under tension and muscle activation. These adaptations, therefore, are critical to practitioners seeking strength and muscle mass gains [28]. In line with this evidence, it has been verified that squatting at a greater depth induces additional hypertrophy in the gluteus maximus and adductor muscles when compared with half squats (knee joint stopping at 90° of flexion) [3]. Thus, it is safe to suggest that using a wedge, as implied in our research, may be a promising approach to allow a greater depth while back squatting.

Regarding the ankle joint, significant differences were determined for dorsiflexion between W25 and W50, with increased RoM in the W50 condition. This result can be explained by the induced plantar flexion caused by the wooden block, which altered the joint kinematics, increasing its RoM. Furthermore, it is essential to mention that the lack of ankle mobility can be a factor contributing to an increase in anterior trunk inclination [29]. Hence, elevating the heel with a wooden block or iron plates could be an alternative to momentarily compensate impaired ankle mobility, inducing a more upright trunk position during back squat execution. With reference to the hip joint, our results were similar to the findings by Legg et al. [12], in which experienced practitioners did not present RoM alterations in this joint with or without the elevated heel. However, the present experiment is the first to report results of the hip joint in the frontal plane. Adduction and abduction RoM were not different between the wedges and barefoot conditions, which suggests that modifications in the heel height impact primarily on the flexion and extension movements in the sagittal plane.

To the best of our knowledge, this is the first experiment to analyse a 50-mm heel height while back squatting, showing an additional benefit compared with the 25-mm elevation. Even though previous analyses are divergent regarding the possible benefits of squatting with weightlifting shoes or a wooden block beneath the heels, most evidence points toward positive adaptions. We must also highlight that our participants had an average of 5-year experience with this exercise. Considering that trained subjects are less sensitive to adaptations because of their higher training levels, elevating the heel during back squat seems a promising strategy to improve movement kinematics. We should also consider that the back squat is used in many training programs, like protocols for rehabilitation [4], elderly functionality [30], and lower limb hypertrophy [2]. Therefore, our results can be applied to a variety of training programs. Our study, however, is not without limitations. The results are restricted to the current study design. It is uncertain whether elevating the heel during back squat would promote similar adaptations in other populations (i.e., women, novices, or older adults) or loading conditions.

Conclusions

We conclude that using a 25- or 50-mm wooden block beneath the heel while back squatting is a viable alternative to weightlifting shoes, leading to a reduced trunk inclination and increased knee RoM in trained males. Hence, a wooden block might be an accessible and low-cost alternative to promote positive adaptations during back squat in a variety of training facilities and programs.

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Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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GOAL ANALYSIS OF THE ENTIRE ITALIAN NATIONAL LEAGUE SERIE A

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ABSTRACT
Purpose. The purpose of this study was to analyse the goals in soccer Italian League Serie A (2018–2019) in relation to (a) the number of total attempts; (b) the time reached; (c) the area from which the final action occurred. Also, the effect of achieving the first goal in the match outcome was studied.
Methods. A total of 380 matches were studied, with 1019 goals scored. All matches were analysed with the SportScout software. Chi-square test was used to find differences between the display frequencies of each variable.
Results. More goals were scored in the second half of the match (χ^2 = 25.438, p < 0.05) and in the last 15 minutes. Most goal attempts were made through the penalty box and outside of it (χ^2 = 2365.002, p < 0.05), though the highest success rates were shown in the attempts from the goal box. Overall, 30% of the total number of goals were scored from set plays (χ^2 = 171.493, p < 0.05), most of them after a corner shot (χ^2 = 18.488, p < 0.05). Furthermore, it appeared that the first goal had a strong impact on the final outcome since in 67.34% of the cases, the team that scored first won the match.
Conclusions. More goals were scored in the second half, especially in the last 15 minutes. Coaches should prepare their players to be fit to cope with the whole match. They will also need to improve their defensive and offensive tactics in set plays.
Key words: Italian League Serie A, goal, video analysis, time period, set play

Introduction

Soccer is one of the most popular sports in the world. At the beginning of the 21st century, more than 250 million athletes were registered, while more than 1.3 billion people were involved in the sport [1]. Match analysis is vital in team sports in order to understand the constraints that promote sporting success [2]. Performance in soccer depends on many factors that interact with one another, such as technique, tactics, and fitness [3]. Match analysis is used to identify the strengths and weaknesses of teams and players in order to improve their performance [4].

Research on international soccer has shown that coaches could only remember 42% of the corrections they had to make during a match [5]. These studies indicate that human memory may not be very reliable for feedback of an event or a match [5]. In turn, an objective assessment derived from video analysis offers, as much as possible, analytical, realistic, and more accurate information illustrating the performance profile of the team and players in real game conditions [6].

One of the most studied variables is the goal because it is critical for the success of a team [4]. Previous studies have reported that the number of goals achieved varies depending on the time of the match [7, 8], with more goals obtained in the second half. Also, if we divide the 90 minutes of the game into periods of 15 minutes, the most goals were scored in the last period (76–90$^+$ min) [7, 9, 10]. Other factors re-

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Table 1. Terms and definition

Term	Definition
Goal	The ball crosses the goal line under the crossbar and the referee awards it
Goal attempt	Kick the ball to the goalpost without the ball being blocked
Free kick	Set play after foul from the opposition, outside penalty box [17]
Penalty kick	Set play after foul from the opposition, inside penalty box [17]
Corner kick	The ball is restored from the corner of the field when an opponent last touched the ball and it crossed the goal line [17]
Pass	A player passes on to a teammate and the ball reaches its destination
Open play	The ball moves and can be claimed by both teams
Set play	Used to get the ball back to a state of open play after foul, corner, penalty [18]

lated to goal are being studied, such as the type and area of the action prior to a goal, the effectiveness of the team, etc. [8, 11].

Another important factor in the performance of a soccer team is the effectiveness in set plays, both in the attack phase and in the defence phase [12, 13]. Other factors have also been studied, such as the effect of the first goal of a match on the final match outcome [8, 11, 14, 15] and the place of the match (home or away) [16]. Although there are several studies on the technical and tactical characteristics of national teams participating in world and European tournaments, research on full national championships is more limited.

The purpose of this study was to analyse all the national competition goals in soccer Italian League Serie A in relation to (a) the number of total attempts; (b) the time reached; (c) the area from which the final action occurred. The place of the match (home or away) and the effect of achieving the first goal on the match outcome were also investigated. It was hypothesized that (a) goal scoring frequency was higher in the second half; (b) most goal attempts were made through the penalty box; (c) most goals were scored from open plays; and (d) the first goal had a strong impact on the final outcome.

Material and methods

Sample

A total of 380 matches of the Italian League Serie A were analysed. Overall, 1019 goals were scored and 7723 final actions (attempts for goals) were performed. These matches were played by 20 teams that participated in the championship during the season of 2018–2019.

Instrument

The soccer matches were videotaped and digitized with a Sony video SLV-SE210D, a PC AMD-XP professional 1333 GHz, and a television capture board for PC (PCTV, Pinnacle Systems GmbH, Braunschweig, Germany). The study was based on the personal observation of one of the researchers, who recorded the time when goals were scored. The SportScout (SportScout STA) video-analysis program for PC was used for the data recording. The operational definitions applied are presented in Table 1.

Procedures

The SportScout software (SportScout STA) allowed to analyse the number of goals per half and every 15 minutes (6 periods: 1–15 min, 16–30 min, 31–45$^+$ min, 46–60 min, 61–75 min, 76–90$^+$ min) [19], whether the goal came in the open play or from a set play, and the effect of the first goal on the match outcome. Also, the number of goals, penalties, own goals, and counter-attacks of home and visitor teams were recorded. The spaces outside and inside the penalty box and inside the goal box were these 3 spaces to distinguish the final actions for goals.

Reliability

To determine the reliability in data recording, the first author of the article recorded all variables from 3 matches. A certified football analyst did the same. The comparison of the data that emerged showed that the recordings of the first author were very reliable. The values of kappa statistic (*r*) test were between 0.97 and 1, i.e. particularly high according to Altman [20]. More specifically:

– the *r* for the number of goals per half and every 15 minutes was 1;

– the r for whether the goal came in the open play or from a set play was 0.99;

– the r for the number of goals, penalties, own goals was 1;

– the r for the counter-attacks of home and visitor teams was 0.97;

– the r for spaces outside and inside the penalty box and inside the goal box that were the 3 spaces to distinguish the final actions for goals was 0.98.

Statistical analysis

The statistical software SPSS 18 (IBM, SPSS Statistics, version 18, Armonk, NY, USA) was used for data analysis. Apart from descriptive statistics, the chi-square test (χ^2) was applied to find differences between the display frequencies of each variable, as well as the effect of the first goal on the match outcome. Statistical significance of the results was accepted at $p < 0.05$.

Ethical approval

The conducted research is not related to either human or animal use.

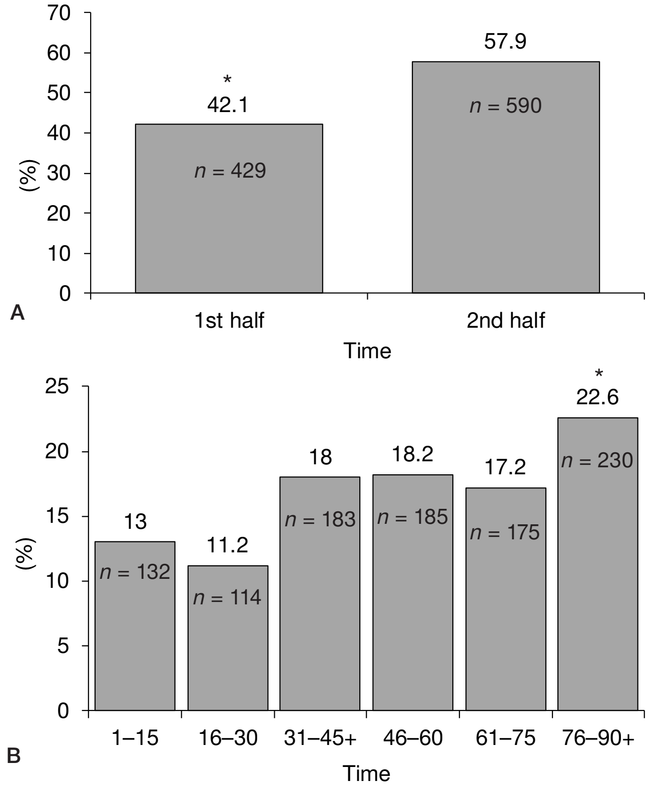
Results

Goals frequency of each half is presented in Figure 1A. The results show that there were significant differences in the number of goals scored between the 2 halves ($\chi^2 = 25.438$, $p < 0.05$). In the first half, 42.1% of goals were scored, and 57.9% of goals were scored in the second half.

Figure 1B depicts the frequency of the appearance of goals in the 6 match periods of 15 minutes. Differences in the frequency of goals occurred between the 6th period (76–90+ minutes) and all the other periods ($\chi^2 = 50.631$, $p < 0.05$). It was found that most goals were scored at the end of the match (22.6%), at the beginning of the second half (18.2%), and at the end of the first half (18%).

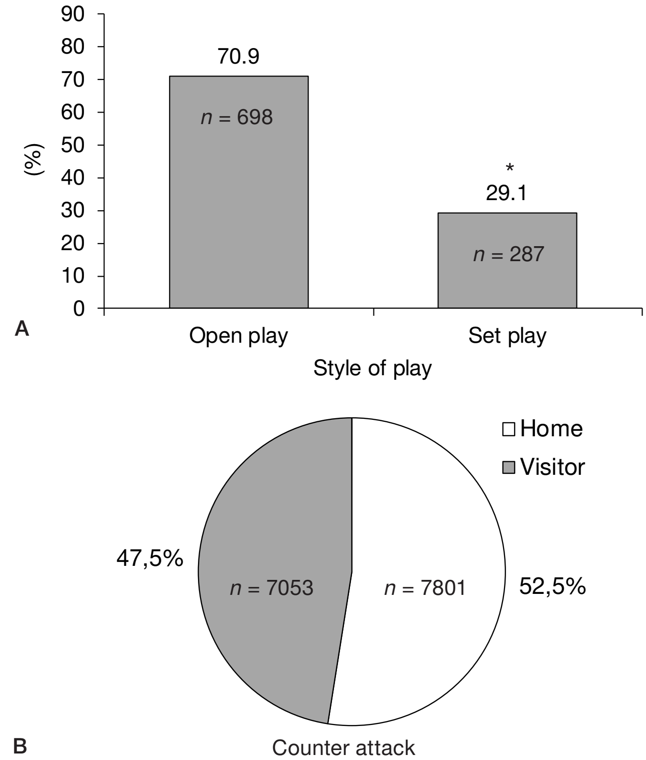
Most goals (698) were scored during open play, while 287 goals during set play ($\chi^2 = 171.493$, $p < 0.05$). Figure 2A shows the differences in frequency by the type of goal. As for counter-attacks, the home teams made 7801 while the visitor teams 7053. These variables are presented in Figure 2B.

Figure 3A shows the frequencies of final actions depending on the space where they occurred. Most final actions were performed in the penalty box and outside the penalty box ($\chi^2 = 2365.002$, $p < 0.05$). Home teams performed 48.4% of their final actions through



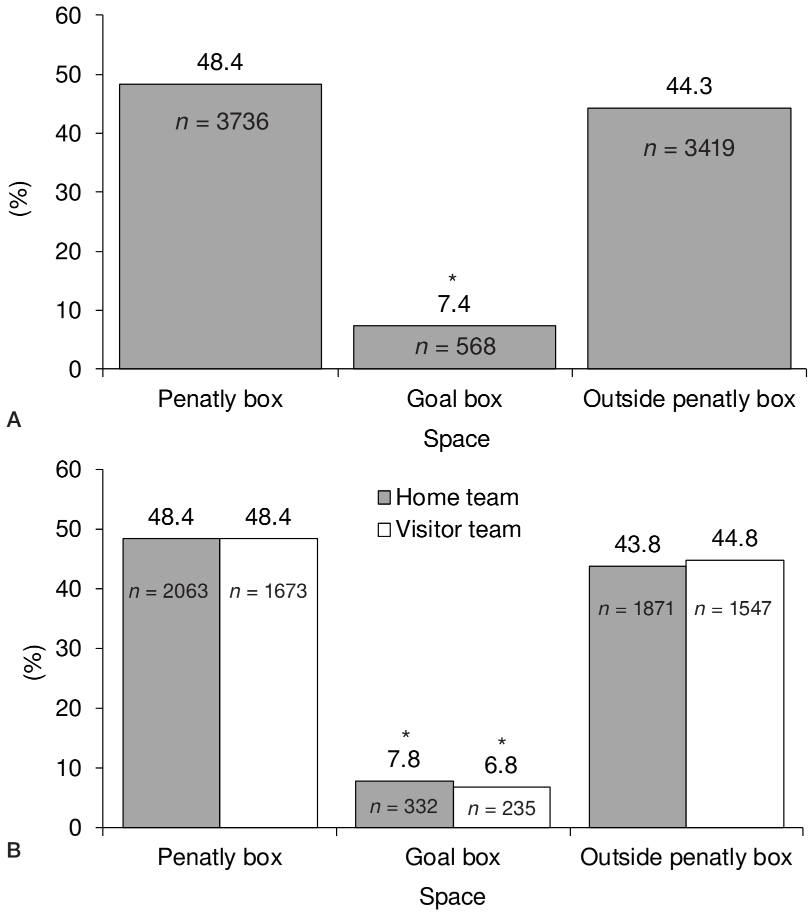
* significant difference with other groups ($p < 0.05$)

Figure 1. Frequency of goals: (A) in the game halves, (B) in the 15-minute periods



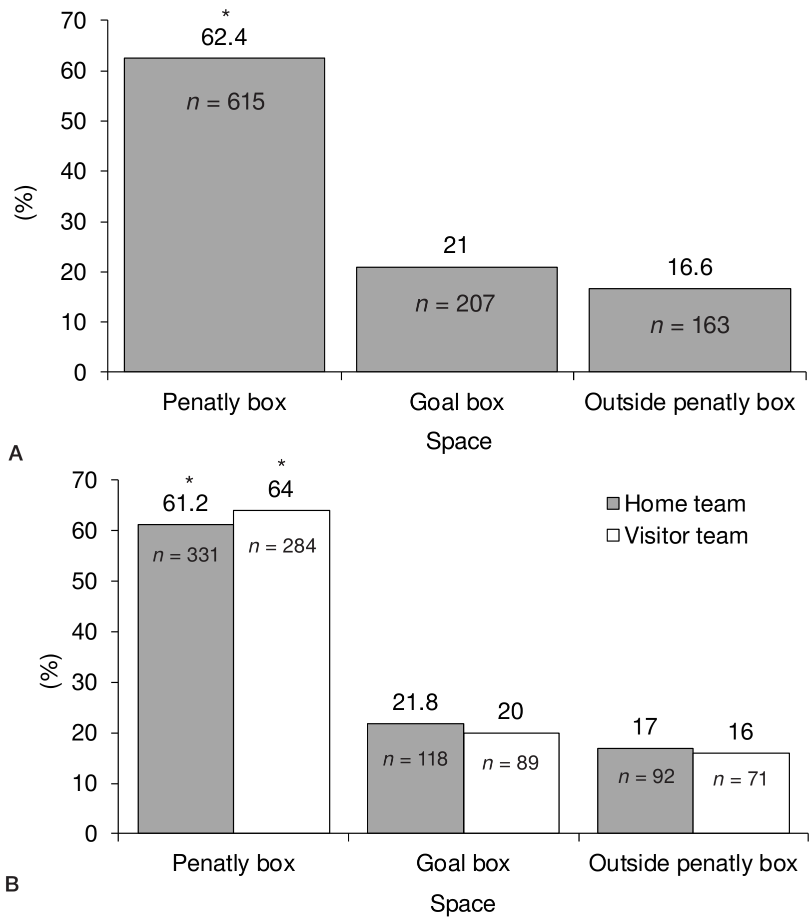
* significant difference with other groups ($p < 0.05$)

Figure 2. (A) Percentages of open play and set play goals (B) Numbers of counter-attacks of home and visitor teams



* significant difference with other groups ($p < 0.05$)

Figure 3. (A) Space of final actions
(B) Space of final actions of home and visitor teams



* significant difference with other groups ($p < 0.05$)

Figure 4. (A) Space of scored goals
(B) Space of scored goals of home and visitor teams

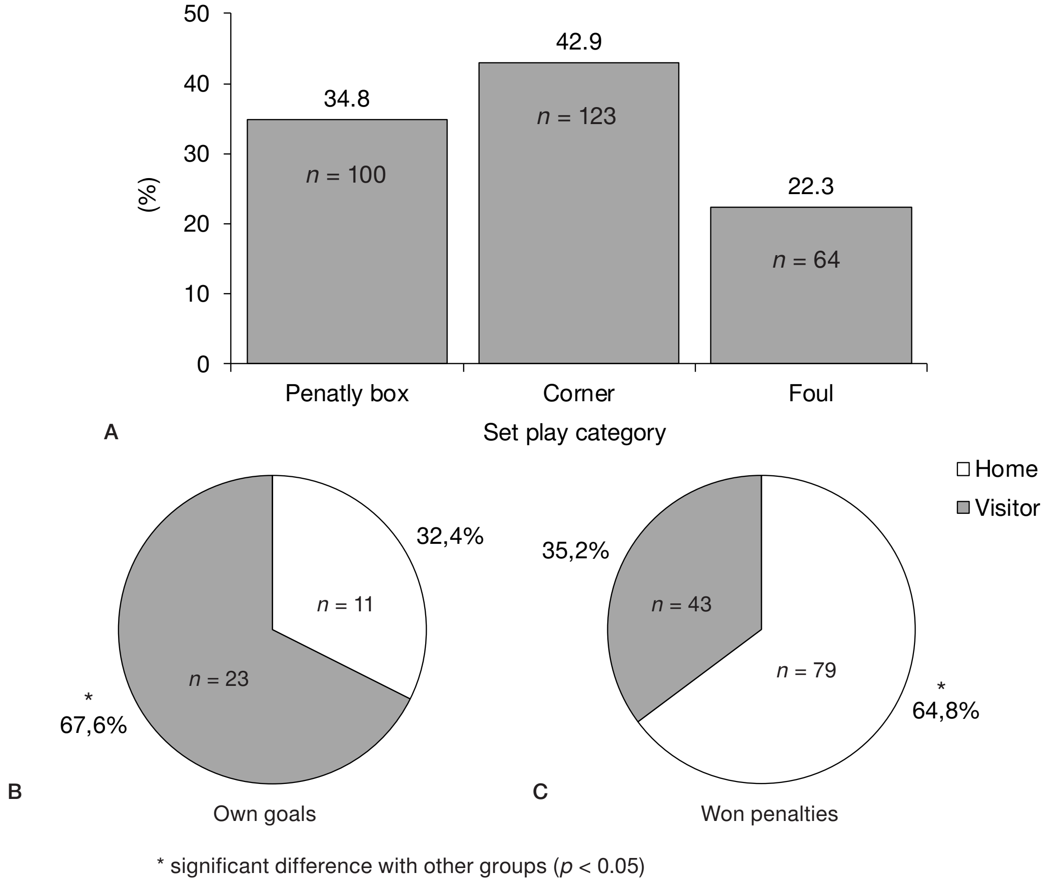


Figure 5. (A) Set play goals
(B) Percentage of own goals of home and visitor teams
(C) Percentage of won penalties of home and visitor teams

the penalty box, 43.8% outside the penalty box, and 7.8% through the goal box (χ^2 = 1266.232, $p < 0.05$). The respective percentages for visitor teams were 48.4%, 44.8%, and 6.8% (χ^2 = 1101.321, $p < 0.05$). Figure 3B shows the frequency of goal attempts and goals from each field area for the home team and visitor team.

Overall, 62.4% of goals were scored from the penalty box, 21% from the goal box, and 16.6% from outside the penalty box (χ^2 = 378.380, $p < 0.05$). Home teams scored 61.2% of their goals from inside the penalty box, while the corresponding percentage for visitor teams was 64%. Home teams scored 21.8% of their goals and visitor teams 20% of theirs through the goal box, whereas the respective percentages for outside the penalty box were 17% and 16%. Differences were observed in both home teams (χ^2 = 190.695, $p <$ 0.05) and visitor teams (χ^2 = 188.554, $p < 0.05$). The frequency differences are shown in Figure 4A, B.

The results show that home teams won more penalties (79) than visitor teams (43) (χ^2 = 10.623, p = 0.001). Also, home teams scored fewer own goals (11) than visitors (23) (χ^2 = 4.235, p = 0.04). In set plays, most goals were scored after corners (123) and penalties (100) compared with fouls (64) (χ^2 = 18.488, $p < 0.05$). The above frequencies are presented in Figure 5A–C.

The study revealed that for the 195 occasions where home teams scored first, they won 143 matches, while for the 151 occasions where visitor teams scored first, they won 90 matches (χ^2 = 240.9, $p < 0.05$).

Discussion

The main objectives of the research were to analyse the goals in soccer Italian League Serie A (2018–2019) in relation to (a) the number of total attempts; (b) the time reached; (c) the area from which the final action occurred. Also, with regard to the place of the match (home or away), goals, attempts to score, and the effect of achieving the first goal on the match outcome were studied. A difference was observed in the frequency of goals scored in relation to the time (match halves, 15-minute periods) and the area from which most final actions were performed. Moreover, differences were found in the frequency of goals between open play and set play. Finally, there were differences between home teams and visitor ones in the number of goals scored and in penalties that they won.

The results imply that more goals were scored in the second half than in the first half. This finding is in line with previous studies carried out in both national leagues [19] and international tournaments involving national teams [14, 15, 21, 22]. The difference is also reflected in the 15-minute periods, where the periods of the second half presented higher frequencies of goals than those in the first half. A high frequency of goals in the 76–90^{+} period has also been reported in previous studies [7, 8, 19, 21, 23].

A goal depends on many factors. So, one cannot accurately point out the cause of this phenomenon. The tactics of the team that is behind the scoring, the tactics of the winning team, the physical and mental fatigue, lack of concentration are all factors that can affect the achievement of more goals in the last minutes of a match. However, in previous studies, it has been reported that fatigue as well as its effect on the concentration of defenders may be an important factor in the emergence of more goals at the end of a match [24]. Similar results were mentioned in a recent study that analysed goals in the English Premier League [19]. More specifically, previous studies have shown that defenders cover shorter distances with high intensity in the last 15 minutes compared with the first 15 minutes, while the corresponding drop for forwards is smaller [25]. Also, it has been reported that fatigue can affect the correct decision making during matches [26]. With these 2 factors, the strikers who find more space to perform their final action seem to be favoured during open play [27].

As far as the area of the final action is concerned, differences were noted with most attempts performed in (48.4%) and outside (44.3%) the penalty box and the least through the goal box (7.4%). Similar percentages were presented for home teams (48.4%, 43.9%, and 7.8%, respectively) and for visitor teams (48.4%, 44.8%, and 6.8%, respectively).

With reducing the distance of the final action from the goalpost, the chance of scoring a goal increased. However, as the opponent approaches the focus, defenders restrict spaces so that it was very difficult for forwards to enter the goal box. Also, when a forward is inside the penalty box, he believes that he is close enough to the goalpost to perform a final action (like a shoot). As the distance from the goalpost increases, the effectiveness of players decreases, though the defence is less pressing, allowing for more final actions. The above fact is reflected in the percentage of goals scored (effectiveness) from the different field areas, with the highest percentage in actions through the goal box (36.4%), followed by actions from the penalty box (16.5%), followed by goals from outside the penalty box (4.8%). Similar percentages were shown for home teams (35.5% for goal box, 16.0% for penalty box, and 4.9% for outside the penalty box) and visitor teams (37.9%, 17.0%, and 4.6%, respectively).

Goals scored from open play constituted 70.9% of the total number of goals. This percentage is similar to those reported in previous studies on the English Premier League [28]. Watching over time, it is found that the percentage of goals scored by open play moves close to 70%. This indicates that a very significant part of the total number of goals are scored by set plays. This suggests that coaches should pay particular attention to the offensive and defensive function of their players during set plays.

Of goals scored during set plays, 42.9% came from corners, 34.8% from a penalty shootout, and 22.3% from fouls. On this basis, it appears that the corner is the most dangerous set play as it resulted in almost twice as many goals scored as compared with fouls. High goal scoring rates from the corner were also mentioned in previous studies [29]. To interpret this observation, we should consider that during corners, forwards occupy spaces in very dangerous positions in front and near the goalpost, so defenders cannot take advantage of the regulation of offside. In turn, in many cases of fouls, defenders take advantage of the regulation of offside by keeping the opposing forwards at a long distance from their goalpost, thereby reducing the chance of conceding a goal. However, in order to get an accurate picture, we need to know the total number of corners and fouls executed by the teams to estimate the effectiveness of each set play.

Among the total number of penalties, 64.8% were given to home teams and the remaining 35.2% to visitor teams. Home teams also scored 11 own goals, while visitors scored 23 own goals. The above percentages reflect particularly the pressure that home teams put on visitor teams to receive a positive match outcome. Teams competing at home, with the encouragement of their fans, probably put more pressure on visitors, forcing them to fall into the penalty shootout or score an own goal. Although we would expect visitor teams to show a higher counter-attack rate per match in this league, it was found that the average number of counter-attacks per match was 20.5 for the home team and 18.6 for the visitor team. Counter-attack can be not only a method for a team's building up in specific match situations, but also the basic offensive tactic of a team, especially when it competes against a higher level team.

Finally, the results showed that the team that scored the first goal gained significant advantage in winning the match, as it was indicated in 73.33% of the cases in which home teams scored first goals and in 59.6% of the cases in which visitor teams scored the first goal, eventually winning the match. A similar effect of the first goal on the match outcome has been reported in previous studies [8, 11, 14, 15, 22]. When a team scores the first goal, there is an improvement in performance and the players present more self-confidence and passion [30, 31]. Moreover, tactical changes with more attention in defence were observed when a team was in the lead [32].

With regard to the limitations of the present study, our analysis was mainly focused on the last action prior to a goal, which means that other important actions of the whole attacking process were not explored. Additionally, variables like team tactics were not considered. This could be an aspect for future studies; capturing so many complex and interactive behaviours prior to a goal would require the use of multiple research methodologies.

Conclusions

The study results showed that in the Italian League Serie A, more goals were scored in the second half, especially in the last 15 minutes. Coaches should prepare their players to be fit to cope with the whole match. This will help players to act more effectively and not to be affected by fatigue. They will also need to improve their defensive and offensive tactics in set plays as 30% of the total number of goals is achieved in this way. One more thing to watch out for is that each team should seek to score the first goal as this can have a significant impact on the final match outcome. However, coaches have to prepare players to deal with a situation in which the opponent takes the lead. Finally, coaches should improve the efficiency of their teams outside the penalty box, probably enhancing both the technique and tactics for the correct selection of conditions for a final action.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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THE RELATIVE AGE EFFECT IN BRAZILIAN ELITE SOCCER DEPENDING ON AGE CATEGORY, PLAYING POSITION, AND COMPETITIVE LEVEL

original paper
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ABSTRACT
Purpose. This study investigated the occurrence of relative age effect (RAE) in Brazilian elite soccer athletes depending on age categories, playing position, and competitive level.
Methods. Data from 2660 male elite soccer athletes who participated in the 2019 Brazilian soccer championships were analysed. To determine RAE, the players were divided by their quarter of birth: Q1 (January-March), Q2 (April-June), Q3 (July-September), and Q4 (October-December). Data were obtained from the Brazilian Soccer Confederation (CBF) official website, and from each club's website when no information was available at the CBF website. Were included the athletes who participated in the 2019 Brazilian soccer championships in series A and B. Data were organized in accordance with age categories (under-20 or senior), playing position (forwards, midfielders, defenders, and goalkeepers), and competitive level (Series A or B).
Results. An overrepresentation of soccer players born in the first quarter of the year was found when compared with the other quarters, whereas players born in the last quarter of the year were underrepresented, regardless of the age category and competitive level. Regarding playing position, an overrepresentation of soccer players born in the first quarter of the year was found for all playing positions in both age categories, except for the goalkeepers in the senior category.
Conclusions. Our results showed a prevalence of RAE in U-20 and senior age categories in elite Brazilian soccer athletes, in both competitive levels, and for all playing positions, except for goalkeepers in the senior category.
Key words: relative age effect, elite soccer athletes, selection process bias, maturation

Introduction

In youth sports organizations around the world, children and adolescents are categorized in accordance with annual age grouping policies. The main purpose of this process is to provide young athletes with fair competition and equal opportunities to develop their skills [1]. However, differences in chronological age within the same age cohort are expected owing to the inherent variability in biological developmental processes [2]. Children born closer to the cut-off date are more likely to be more developed in cognitive, psychological, and physical aspects than players born further from the cut-off date [2, 3]. The consequences generated by the chronological differences among athletes in the same age group are known as the relative age effect (RAE). In this regard, RAE provides an immediate competitive advantage, within the same age group, to relatively older players and disadvantages for relatively younger athletes, which can be reflected in higher dropout rates and lower chances to achieve long-term success in sport [4, 5].

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RAE is a widespread phenomenon across many sports, especially team sports [3, 6, 7]. This effect manifests to a greater extent in young male athletes, especially in highly competitive contexts [1, 3, 8]. Thus, as it could be expected, RAE is well established in the Brazilian youth soccer [9–11], where a large pool of athletes competes for a limited number of spots. Since soccer is a sport characterized by high physical and physiological demands [12, 13], coaches are biased towards selecting those athletes who present better developed physical attributes. One aspect to consider is that inter-individual variations related to growth and maturity are especially pronounced in infancy and adolescence [2], that is, when talent selection processes usually occur. Consequently, relatively older athletes are more likely to progress in sport than relatively younger players because of a 'biased' view of their real potential [3].

The primary mechanism that explains the occurrence of RAE as a bias factor in the early stages of the athletes' development process is the role of physical maturation (i.e. maturation-selection hypothesis) [3]. Although the RAE phenomenon exists, its consequences tend to disappear when the age category and competition level increase, and the athletes have already gone through the growth spurt (e.g. under-20 and senior). Nevertheless, sometimes RAE is so pervasive in youth categories that it remains up to U-20 and even senior categories [5, 7, 14, 15]. This phenomenon may cause the systematic loss of potential sporting talents as a result of biased decisions made in the earlier age categories.

RAE is a multifactorial phenomenon in nature, and many aspects associated with the individual, the environment, and the task constraints provide a theoretical rationale to explain its occurrence in different sports contexts [8]. Among several aspects, the relationship between playing position and RAE has received attention in recent years. In soccer, some studies were carried out to verify whether the specific demands of each playing position could modulate the occurrence of RAE. Romann and Fuchslocher [16] addressed this matter in elite Swiss junior soccer players and found that relatively older defenders were overrepresented compared with the other playing positions, suggesting that RAE might be determined by playing position. Conversely, Campos et al. [14] investigated elite U-20 South American soccer athletes and observed RAE in all playing positions, except for goalkeepers. Thereby, to date, the effect of playing position on RAE in soccer is still controversial and seems context-dependent. Hence, the relationship between RAE and playing positions remains a topic to be addressed in the Brazilian soccer system.

Another factor that may modulate RAE is the competitive level. Overall, the most skilled players are expected to play in more competitive tiers (Series A in the case of Brazilian soccer). The lower divisions (Series B), on the other hand, could serve as back doors for the first-tiers competitions, being especially important for players who might have previously been neglected owing to maturational aspects [5]. Aiming to verify whether the second tiers leagues indeed represented a second opportunity for late-born athletes, Rađa et al. [5] investigated RAE in first and second tiers leagues in 5 of the most prestigious European soccer leagues. The results indicated that RAE occurred in the same magnitude in both tiers, which may reduce the chance for late-born athletes to reach first tiers leagues.

Despite the fact that RAE is a widely investigated phenomenon in soccer, most research on this topic referred to European leagues [17, 18]. The European context has different characteristics from Brazil with regard to organizational structure, competitive level, selection, training, and development of talents for soccer. To illustrate, recent evidence indicates that Brazilian players born in the first 6 months of the year, from cities with a demographic rate of up to 100,000 inhabitants and a Human Development Index above 0.501, are more likely to reach the elite of Brazilian soccer (Series A) [19]. Considering that the occurrence and magnitude of RAE seems to be directly influenced by environmental constraints [8], it is relevant to explore how this phenomenon manifests itself in the Brazilian soccer context. This is particularly necessary because studies that investigated RAE among Brazilian elite soccer athletes are limited. Costa et al. [20] studied RAE depending on the competitive level (Series A and B) in the 2008 elite Brazilian championship and confirmed the presence of this effect in both tiers of competition. More recently, a historical analysis that comprised a wide sample of players born in years 1921–1996 showed that RAE was present in the Brazilian soccer system during the decades of 1960s, 1970s, 1980s, and 1990s [21]. However, current data on RAE existence among elite athletes in the Brazilian soccer are scarce in the literature. Additionally, to the limit of our knowledge, previous studies did not account for the players' competitive levels, playing positions, and age categories together, precluding specific conclusions regarding the roles of these aspects on RAE occurrence in the Brazilian soccer system. A broad analysis of RAE among Brazilian elite players has important practical implications for different reasons. Soccer is a sport played by millions of children and teenagers in the country. The institutional policies used by federations and methodological approaches applied by professionals during the selection of young athletes can influence the formation and development of talents for the sport. Sports systems in which RAE is predominant may result in the loss of potential talents because of inequalities generated by age grouping systems based on athletes' birthdates [1, 3, 22]. Therefore, investigating how RAE manifests depending on age category, playing position, and competitive level is crucial to reduce potential inequalities in the Brazilian soccer system.

This study aimed to investigate the existence of RAE in Brazilian elite soccer athletes from U-20 and senior categories. Moreover, we sought to observe whether playing position and competitive level were associated with RAE. We hypothesized that RAE would be found in athletes from both age categories, with a smaller effect in the senior category, with small expected maturation differences [2]. Moreover, we expected to verify RAE regardless of playing positions or competitive level, owing to the highly competitive nature of the Brazilian soccer system, which increases the likelihood of RAE [1].

Material and methods

Participants

The sample of this study was composed of 2660 male elite soccer athletes who were part of the U-20 (mean age: 18.6 ± 1.1 years) and senior (mean age: 26.0 ± 4.9 years) squads of professional teams that participated in the 2019 Brazilian soccer championships, in series A or B (first and second tiers of the Brazilian soccer championships, respectively). The athletes were organized by the variable analysed as follows: age category (U-20, n = 1471; senior, n = 1189); competitive level (series A, n = 1399; series B, n = 1261); playing position (forwards, n = 647; midfielders, n = 902; defenders, n = 837; goalkeepers, n = 274).

Data collection and procedures

Data were obtained from rosters available at the Brazilian Soccer Confederation (CBF) official website (www.cbf.com.br). When no information was available at the CBF website, the clubs' websites were consulted. Data collection was performed in January 2019. The information obtained included players' full names, dates of birth, playing positions, and age categories. Athletes whose information was incomplete were not considered for the study.

The cut-off date for youth categories of teams participating in the Brazilian soccer championships is January 1 (quarters are composed as a function of this cut-off). The variables analysed included the quarters of the year the athletes were born: Q1 (January, February, March), Q2 (April, May, June), Q3 (July, August, September), and Q4 (October, November, December), and were split depending on age categories (U-20 and senior), competitive levels (Series A and B), and playing positions (forwards, midfielders, defenders, and goalkeepers). Players who composed a squad in more than one category were considered only once in the analysis, on the playing position they played in the senior category.

Statistical analysis

Athletes' frequencies were presented in absolute and relative values. We analysed the occurrence of RAE among players by comparing the frequency of athletes born in each quarter observed in our sample and the frequency expected (Exp) for the Brazilian population on the basis of Brazilian reports. This is a methodological procedure traditionally used in the RAE literature with the purpose of minimizing the bias associated with seasonal variations in the birth rate between months of the year [22, 23]. Thus, in our analysis, we considered the number of births in each quarter of the year based on Brazilian reports from 1994–2001 (Brazilian Ministry of Health), which led to the following expected observations for each quarter: Q1: 25.7%, Q2: 26.3%, Q3: 24.8%, and Q4: = 23.2%.

A chi-square test (χ^2) was performed to compare the athletes' birthdates distribution depending on sex, event type, and age category. For all analyses, the effect size (ω) of the chi-square tests was calculated. Additionally, odds ratio (*OR*) and 95% confidence interval for Q1 vs. Q4 and first semester vs. second semester were calculated. Analyses were performed in the Statistical Package for the Social Sciences (SPSS), version 20.0 (Chicago, USA). The level of significance was 0.05. Whenever multiple comparisons between quarters were necessary, Bonferroni's corrections were performed. In these cases, the significance level was adjusted to 0.008.

Ethical approval

The conducted research is not related to either human or animal use.

Results

Birthdate distribution by quarters

Figure 1 shows the relative frequency of the observed and expected birthdate distribution of the pooled Brazilian soccer players. Our analysis indicated an uneven distribution of birthdates ($p < 0.001$; ω = 0.33; Q1 = 970; Exp = 682.6; Q2 = 830; Exp = 701.4; Q3 = 502; Exp 660.5; Q4 = 358; Exp = 615.5). Players born in the first 3 months of the year were overrepresented compared with those born in the other quarters ($p < 0.001$; *OR* Q1:Q4 = 3.69; *OR* S1:S2 = 4.38). Moreover, players born in the last 3 months of the year were less frequent than athletes born in all the other quarters ($p < 0.001$).

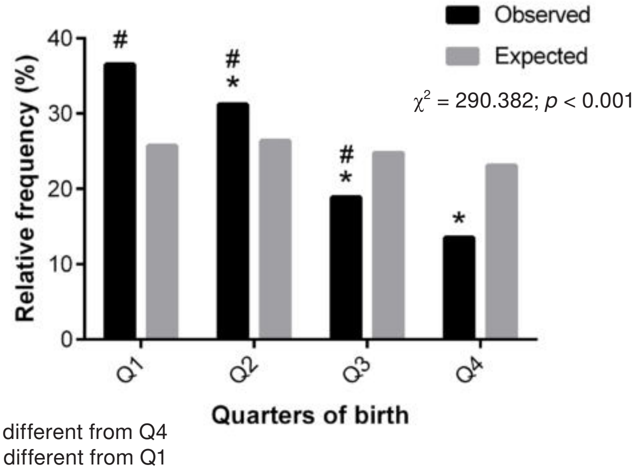

Figure 1. Relative observed and expected birthdate frequencies of elite soccer athletes

Relative age effect vs. age categories

When athletes were analysed by age categories (Table 1), the chi-square analysis indicated uneven birthdate distributions in both U-20 ($p < 0.001$; ω = 0.42) and senior ($p < 0.001$; ω = 0.21) age categories. In the U-20 category, athletes born in the first 3 months of the year were overrepresented in comparison with those born in the last 3 months of the year ($p < 0.002$). In addition, players born in the last 3 months of the year were less frequent than those born in the other quarters of the year ($p < 0.002$). In the senior category, athletes born in Q1 ($p < 0.001$), Q2 ($p < 0.001$), and Q3 ($p < 0.007$) were overrepresented in comparison with those born in the last 3 months of the year.

Relative age effect vs. competitive level

When athletes were analysed by age category and competitive level (Table 2), the chi-square analysis indicated that players born in the first semester of the year were overrepresented in both age categories and competitive levels ($p < 0.001$). However, the magnitude of this overrepresentation was larger in the U-20 category, in both competitive level A and level B (ω = 0.46, ω = 0.36, respectively), than in senior players (ω = 0.196, ω = 0.23, respectively). Overall, athletes born in Q1 and Q2 were more frequent than those born in Q4 ($p < 0.001$), regardless of the age category or competitive level. However, it was only in the U-20 category that players born in Q4 were less frequent than those born in all the other quarters of the year ($p < 0.005$).

Relative age effect vs. playing position

When players were analysed by their age category and playing position (Table 3), the chi-square analysis indicated that athletes born in the first semester were more frequent in all playing positions in both U-20 ($p < 0.001$) and senior ($p < 0.001$) categories, except for the goalkeepers in the latter ($p = 0.89$). For all the other playing positions, athletes born in the first semester were more frequent than those born in the last 3 months of the year ($p < 0.003$). The magnitude of the effect was larger in U-20 forwards (ω =

Table 1. Brazilian senior and U-20 soccer players' birthdates distribution by age category

Category	Q1	Q2	Q3	Q4	χ^2	*p*	ω	*OR* Q1:Q4	*OR* 1st:2nd
	(Exp)	(Exp)	(Exp)	(Exp)				95% CI	95% CI
Senior	390[c,d] (305.5)	353[c,d] (313.9)	243[d] (295.4)	203 (274.3)	56.745	< 0.001	0.218	2.37 1.95–2.88	1.96 1.67–2.31
Under-20	580[b,c,d] (377.5)	477[c,d] (387.9)	259[d] (365.2)	155 (340.4)	261.025	< 0.001	0.421	5.53 4.54–6.73	6.52 5.55–7.66

Q – birth quarter, (Exp) – expected distribution, ω – effect size, *OR* Q1:Q4 – odds ratio from Q1 to Q4, *OR* 1st:2nd – odds ratio from 1st semester to 2nd semester, [b] different from Q2, [c] different from Q3, [d] different from Q4

Table 2. Brazilian senior and U-20 soccer players' birthdates distribution by series played

Series	Category	Q1 (Exp)	Q2 (Exp)	Q3 (Exp)	Q4 (Exp)	χ^2	*p*	ω	*OR* Q1:Q4 95% CI	*OR* 1st:2nd 95% CI
A	Senior	180c,d (145.2)	168c,d (149.3)	119 (140.5)	99 (131)	21.781	< 0.001	0.196	2.199 1.66–2.91	2.548 2–3.24
	Under-20	342b,c,d (213.7)	272c,d (219.7)	140d (206.8)	79 (192.8)	178.154	< 0.001	0.462	6.648 5.08–8.70	7.86 6.32–9.78
B	Senior	210c,d (159.9)	185c,d (164.3)	124 (154.7)	104 (144.2)	35.615	< 0.001	0.239	2.537 1.94–3.32	3.001 2.38–3.78
	Under-20	238c,d (163.7)	205c,d (168.2)	119d (158.4)	76 (147.6)	86.307	< 0.001	0.367	4.399 3.3–5.87	5.048 3.98–6.40

Q – birth quarter, (Exp) – expected distribution, ω – effect size, *OR* Q1:Q4 – odds ratio from Q1 to Q4, *OR* 1st:2nd – odds ratio from 1st semester to 2nd semester, b different from Q2, c different from Q3, d different from Q4

Table 3. Brazilian senior and U-20 soccer players' birthdates distribution by playing position

Category	Position	Q1 (Exp)	Q2 (Exp)	Q3 (Exp)	Q4 (Exp)	χ^2	*p*	ω	*OR* Q1:Q4 95% CI	*OR* 1st:2nd 95% CI
Senior	ATK	91c,d (72.1)	88d (74.1)	56 (69.8)	46 (65)	15.843	0.001	0.237	2.45 1.64–3.66	3.08 2.18–4.343
	MDL	136c,d (101.9)	120c,d (104.7)	76 (98.6)	65 (91.9)	26.701	< 0.001	0.259	2.66 1.90–3.73	3.3 2.46–4.41
	DEF	128d (97.5)	108d (100.2)	80 (94.4)	64 (87.9)	18.839	< 0.001	0.223	2.51 1.78–3.53	2.69 2.04–3.60
	GLK	35 (33.6)	37 (34.5)	32 (32.5)	27 (30.3)	0.602	0.896	0.067	1.4 0.79–2.49	1.49 0.92–2.42
U-20	ATK	151c,d (93.9)	116c,d (96.5)	64d (90.9)	35 (84.7)	75.737	< 0.001	0.455	6.86 4.56–10.31	7.27 5.25–10.08
	MDL	186c,d (117.3)	186c,d (120.5)	78 (113.5)	55 (105.7)	96.177	< 0.001	0.436	4.77 3.42–6.65	7.82 5.91–10.35
	DEF	186b,c,d (129.6)	131c,d (133.2)	89d (125.4)	51 (116.9)	74.824	< 0.001	0.405	5.46 3.87–7.71	5.13 3.87–6.79
	GLK	57c,d (36.7)	44d (37.7)	28 (35.5)	14 (33.1)	24.887	< 0.001	0.417	6.11 3.22–11.56	5.78 3.48–9.62

Q – birth quarter, (Exp) – expected distribution, ω – effect size, *OR* Q1:Q4 – odds ratio from Q1 to Q4, *OR* 1st:2nd – odds ratio from 1st semester to 2nd semester, ATK – attacker, MDL – midfielder, DEF – defender, GLK – goalkeeper
b different from Q2, c different from Q3, d different from Q4

0.45), midfielders (ω = 0.43), defenders (ω = 0.40), and goalkeepers (ω = 0.41) when compared with senior forwards (ω = 0.23), midfielders (ω = 0.25), defenders (ω = 0.22), and goalkeepers (ω = 0.06).

Discussion

In the present study, we investigated the presence of RAE in Brazilian elite soccer athletes from U-20 and senior categories and analysed whether playing position and competitive level were associated with RAE. As predicted, our main findings confirmed the existence of RAE among athletes in both age categories (more pronounced in the U-20 category), both competitive levels (Series A or B), and all playing positions, except for goalkeepers in the senior category. These observations corroborate those from previous studies with elite soccer athletes both in Brazil [11, 21] and worldwide [5, 18]. Moreover, this study indicated different RAE magnitudes in U-20 and Senior Brazilian National Soccer League athletes, depending on playing position and competitive level. Since RAE occurs in Brazilian elite soccer athletes, coaches and stakeholders are warranted to implement counter-RAE interventions, aiming to reduce the loss of potential sporting talents because of inequalities resulting from the age grouping system.

In our study, RAE of different magnitudes was found in U-20 and senior categories (ω = 0.42, ω = 0.21, respectively). Even though RAE decreased as age categories increased in our study, it was still present in both age categories, which indicates that athletes' birthdates continue to play an important role in the selection of elite players, even in the senior category [3]. This seems to be associated with the pressure for immediate results imposed on coaches of Brazilian youth categories [24]. Indeed, previous studies have consistently shown that Brazilian youth coaches are more likely to select relatively older players, as they may achieve higher performance in the short term [10, 25]. Nevertheless, the reduction in the magnitude of the effect suggests that selecting supposedly more physically developed athletes in younger categories because they are relatively older does not represent great advantages for the insertion of players in the senior level. In fact, the reduction of RAE magnitude as the categories advance indicates that a significant proportion of young athletes born closer to the cut-off dates are not reaching the senior category. This idea has already been reported in the Brazilian soccer context, along with the notion that relatively younger athletes may actually benefit in the long run from competing with relatively older peers [24].

The reduction in the magnitude of the RAE with the increase in age category may be a result of the interaction between several factors (e.g. technical, tactical, and psychological aspects) that are warranted to influence elite athletes' selection and adherence in older age categories [3, 15]. It has been proposed that relatively younger athletes may benefit from competing with relatively older peers [5]. Since relatively older athletes are more likely to be bigger, faster, and stronger, relatively younger athletes need to develop other resources to thrive in this disadvantaged environment. The constant competition with older peers, however, may result in the development of more skilled players, which in the long-term could provide younger players with a greater chance of success if they ever manage to reach the senior category [5]. In line with these propositions, Ramos-Filho and Ferreira [24] identified a reverse RAE concerning sports performance in professional Brazilian soccer players. Similarly, Ashworth and Heyndels [26] demonstrated that relatively younger German soccer players tended to earn higher wages when they reached the professional league. Taken together, these results suggest that coaches must account for factors other than age-related differences in the early selection of elite athletes.

The analysis of players by the competitive level showed that RAE was present in both divisions, regardless of the age category. The analysis of the odds ratios, however, indicated a contrary trend for the magnitude of the effect in the U-20 and senior categories. In the U-20 category, players born in the first semester were 7.86 times more likely to be part of Series A squads than those born in the second semester (*OR* = 5.05 in Series B). On the other hand, in the senior category, players born in the first semester were 2.55 times more likely to be part of Series A squads than those born in the second semester (*OR* = 3.0 in Series B). These results indicate that the composition of Series A in the U-20 squads seems to have greater remnants of decisions made by coaches in lower categories, based on possible advantages in the development stages. Conversely, in the senior category, the opposite occurs, since fewer relatively younger players compose Series A squads compared with Series B squads. Since the most skilled athletes (not necessarily those who are bigger and stronger) are expected in a greater proportion in the Series A teams, these results indicate that over time, there seems to be a natural re-evaluation of players [5]. This correction, via the athletes' transfer market, seems to reposition the younger athletes to more qualified teams in the senior category.

The playing position analyses indicated an overrepresentation of relatively older players in all the line playing positions (i.e. forwards, midfielders, and defenders), in both age categories. Once again, higher magnitude effects were found in the U-20 category (medium-sized effects) rather than in the senior category (small-sized effects). These analyses also imply that effects were similar among positions in the U-20 and all line positions in the senior category. Our results are different from those obtained by Salinero et al. [27], who only found RAE in some of the playing positions, which varied depending on the different European leagues investigated. Overall, evidence reinforces the notion that RAE is multifactorial [8] and that the results found in playing position analysis are context-dependent. We assume that the prevalence of RAE in most playing positions in our study is a consequence of the high competition for spots as line players in Brazilian soccer because of the high popularity of this sport. The prevalence of RAE in all line positions also follows the current soccer physical demands. Since elite soccer increasingly demands high game intensities [28], faster and stronger athletes tend to be preferred in all line positions. This could explain why youth coaches continuously favour relatively older athletes since they are more likely to show increased physical performance earlier, owing to maturation [17].

An exception was the case of goalkeepers since RAE was not found in this position in any age category investigated in this study. This finding is in line with the observations by de Souza et al. [29], who also did not report RAE for elite senior Brazilian goalkeepers. One of the explanations provided by these authors to these results is based on the greater prestige and financial gains provided by line positions, which would make young athletes more prone to compete for spots in these positions rather than for goalkeeper spots in younger categories. Our results provide some advances in this discussion since RAE on the goalkeeper position was only verified in the U-20 category, but not in the senior category. The absence of RAE in elite Brazilian goalkeepers seems to be specific to the senior category, and not to result from low competitiveness in the grassroots categories. The lack of RAE elimination in goalkeepers from the senior category is likely due to the specificity of the skills, training, and selection in this position [30]. The presence of goalkeepers' coaches and trainers in the selection processes and throughout the development of sports talents may minimize the focus on maturational aspects and promote the emphasis on the position-specific skills, aiming at long-term development [29]. Furthermore, the goalkeepers' careers tend to be longer, with their peak performance reaching later than in line players [30]. These facts demonstrate that in this position, the players need more time to develop specific skills, which allows the valuation of aspects other than maturation in the selection processes. To confirm these hypotheses, future longitudinal studies are warranted to further understand the role of RAE among goalkeepers.

One of the limitations of the present study was that data were collected in a single moment in time, comprising male athletes who were part of squads participating in the 2019 Brazilian soccer championships. This precluded an overview of the phenomenon in elite soccer athletes, allowing the rather specific context of RAE in the Brazilian soccer league only. Also, we did not control the effective participation times of athletes in the competitions, only their registration in CBF to participate in a squad. This information could provide important insights into the effects of RAE not only on selection but also on the athletic development opportunities received by athletes depending on their birthdates [31]. Future investigations are warranted to overcome these limitations by using longitudinal approaches and by controlling the participation of athletes in official matches.

Conclusions

In summary, RAE is present in U-20 and senior age categories in elite Brazilian soccer athletes, in both competitive levels and all playing positions, except for goalkeepers in the senior category. This indicates that relatively older athletes are systematically favoured in the Brazilian youth soccer system, owing to developmental advantages that might cause better performance in the short term [25]. These results have important practical implications for the development of talents in Brazilian soccer, especially regarding the athlete selection processes. Since research has consistently shown that this selection bias in the early stage of athletes' development is not associated with long-term sports achievements [32], counter-RAE policies are necessary to minimize the loss of potential sports talents. Some interventions in this direction have been proposed, such as educating coaches about RAE incidence in soccer systems [1]; using numbered shirts depending on birthdates during tests to highlight chronological differences between players [33]; and changing the regulations in youth soccer competitions, including the mandatory registration of a minimum number of athletes born in the second semester [5].

A paradigm shift in youth categories is necessary to reduce the extensive RAE in the Brazilian soccer context, as coaches and stakeholders should place less investment in the short-term pursuit for sporting achievements in these categories. As long as coaches feel the pressure to win competitions in the grassroots categories, they are likely to favour relatively older young athletes, as they tend to be bigger and stronger [6]. In this sense, technical, tactical, and psychological aspects that are so important in elite-level sport become secondary factors when it comes to selection and playing opportunities. Unless long-term talent development policies are implemented in Brazilian soccer, the inequalities generated by RAE will tend to be maintained in this sports system, even reaching the senior category.

Disclosure statement
No author has any financial interest or received any financial benefit from this research.

Conflict of interest
The authors state no conflict of interest.

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RINK HOCKEY TEAM PERFORMANCE AND TECHNICAL DETERMINANTS OF THE GAME: A FULL-SEASON ANALYSIS

original paper
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ABSTRACT
Purpose. This study aimed to analyse the correlations between individual technical determinants and the overall team performance in rink hockey sport.
Methods. Retrospective observational data were collected from 182 matches played by 14 teams competing at the first division of the Portuguese national senior rink hockey championship (full season, 2018/19). Goals scored, goals conceded, direct free-hits, penalties, and final classifications were collected by team, on the basis of the official scoresheets of the games, validated by the official referees.
Results. The results revealed that direct free-hits were more prevalent, although teams were more effective on penalties (40.4%) than direct free-hits (27.1%). Strong inverse relationships between direct free-hits effectiveness and final classification in the league ($r = -0.71$, $p = 0.004$) as well as penalties ($r = -0.58$, $p = 0.029$) were found. The effectiveness of the technical determinants, penalties, and direct free-hits increased with the proficiency of the teams in the classification. However, the bottom teams experienced significantly higher weights of these technical determinants on the team's total goals scored (1^{st}–4^{th}: 15.3%, 5^{th}–9^{th}: 25.6%, 10^{th}–14^{th}: 23.9%; $p < 0.05$).
Conclusions. In conclusion, individual technical determinants' effectiveness was a strong predictor of team performance, accounting for at least 22.1% of the total goals scored in the full season, highlighting athletes' specialization in the training process.
Key words: rink hockey, match analysis, direct free-hits, penalties, effectiveness, technical performance

Introduction

Team sports practitioners have been progressing their knowledge in relation to the individual and technical determinants needed to outperform their opponents by observing and analysing the training- and match-related physical, technical, and tactical demands, which has led to the development of match analysis systems to collect and gather data from various sports [1]. In an environment of extreme competitivity, these data analyses could be crucial for determining and identifying training and match weakness and strengths (at both the individual and team levels) that must be improved during the training process [2].

Despite the lack of research regarding rink hockey, efforts have been made to understand the demands of this team sport. Such efforts have demonstrated a common pattern of typical intermittent demands [3], where it is expected that players have to deal with performance stressors such as sprints with high accelerations and decelerations and changes of direction, resulting in its high-intensity nature, as it has been well-documented in other team sports, such as soccer, handball, basketball, and futsal [4–8].

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Rink hockey, as any other team sport, is characterized by its complex dynamic system [3] in which players are expected to engage in interactions of order vs. disorder between them that may affect their behaviours throughout the game, as well as the final outcome of the match [9]. Considering the dynamic and uncertain nature of the behaviours (and for the purpose of performance analysis of this sport), the roller-hockey indoor field area has been divided into 3 corridors (left, right, and centre), 6 areas, and 18 zones [10]. Areas 1 and 2 are the defensive areas; areas 3 and 4 are the intermediate areas; and areas 5 and 6 are the definition areas, which are where the players' role actions occur during a match.

With the aim to analyse the goalkeepers' performance, Sousa et al. [10] found that the goalkeepers tended to be more effective during the first half than the second half, which might be caused by the levels of physical and mental fatigue that occurred during the match, thus decreasing goalkeeper performance determinants in the late phases of the match, as previously documented in other studies related to soccer [11]. Because of the aforementioned mental and physical fatigue – and the game-specific rules regarding faults accumulation during the second half – opportunities for direct free-hits increase as the match progresses. Further, recent research has revealed that goalkeepers are more effective in defending direct free-hits when they use the technique of moving their arms and when they assume a squatting position with a knee on the floor. Also, goalkeepers were less effective in defending direct free-hits when converted by left-handed players [12].

The team performance depends on the interaction between players on the field, supported in different moments that characterize the game: positional attack, positional defence, transitions, period of inferiority, and free shots (penalty and direct free-hit). Recent research on similar team sports (e.g., soccer, basketball, handball, futsal) has described the moments of the game when the offensive playing style of a team and offensive transitions tend to favour goal scoring for the attacking team, as well as the analysis of global performance [13–16].

Even though rink hockey is played by many athletes around the world, little is known about this sport, and the empirical knowledge of rink hockey is supported only in practice and through experience. Moreover, performing penalties and direct free-hits gives players more chances to score when compared with indirect free-hits and other moments of the game (e.g., during positional attacks and periods of inferiority), proving the importance of match analysis and previous observation. Moreover, to the best of our knowledge, specific metrics on this topic are innovative and helpful to coaches when designing training sessions.

Therefore, considering the complexity of this game, this paper analyses the correlations between team performance and individual technical determinants of rink hockey game actions. The findings may allow coaches to periodize training in accordance with the specific match demands and typical behaviour patterns of play.

Material and methods

Sample

In this study, 182 matches played by 14 teams were analysed. The teams competed in the first division of the Portuguese national hockey championship organized by the Portuguese Roller Sports Federation (Federação de Patinagem de Portugal, FPP) [17] during the 2018/19 season. As such, this cohort study includes a retrospective observational data collection for a full season.

Materials and procedures

For data collection, the FPP website was used [17], which contains all the official match details, including official spreadsheets of the games validated by the referees nominated by the FPP and available to the public. The data were subdivided into 3 parts: (1) the first round of the championship; (2) the second round of the championship; and (3) the entire championship. Data for the full 2018/19 season were collected retrospectively by 2 trained coaches of level II and III specific of rink hockey sport. As outcomes of interest, variables such as goals scored, goals conceded (and the ratio between these 2 variables), direct free-hits, penalties, and final classifications were analysed. Data from each team participating in the Portuguese championship were considered. In addition, the set pieces of each team (i.e., converted and unconverted penalties in favour and against each team and converted and unconverted direct free-hits in favour and against each team) were investigated.

On the basis of the final classification of data collected from the 2018/19 season, stratification in 3 different groups was carried out in accordance with the rankings in the competitive table, which are as fol-

Table 1. Descriptive statistics of total goals scored, penalties, and direct free-hits converted over the full season

Descriptive data among 14 teams	Mean (*SD*)	Min.	Max.
Total goals scored	95.1 (26.0)	64	150
Total penalties in favour	20.8 (4.7)	15	29
Converted penalties in favour	8.4 (2.5)	4	14
Ratio penalties converted:total goals scored (%)	9.2 (3.3)	5.6	18.0
Total free-hits in favour	42.8 (11.2)	23	59
Converted free-hits in favour	11.6 (3.6)	3	17
Ratio free-hits converted:total goals scored (%)	12.9 (5.2)	4.0	21.5
Ratio converted penalties and free-hits:total goals scored	22.1 (5.7)	12.4	30.4

lows: (i) champions (1st–4th); (ii) CERS (Confédération Européenne de Roller Skating) (5th–9th); (iii) others (10th–14th). This stratification served to analyse the technical determinants efficacy, weight on total goals scored, and final classification of the championship.

Statistical procedures

The results were expressed as mean (standard deviation) for descriptive statistics. For efficacy calculation (%), converted set pieces were considered divided by the total situations of a specific technical determinant (direct free-hits and penalties) or total goals of the season (weight on the total goals scored). To test the reliability between the 2 coaches, kappa coefficients (k) were calculated for the outcome variables of interest (above 0.90), indicating an almost perfect level of agreement.

The data followed normal distribution and Pearson bivariate correlations were used to analyse the relationship of the efficacy of offensive direct free-hits and penalties with the final classification in the league. As implied in the literature [18], the magnitudes of correlations were classified as trivial (0.0–0.1), small (0.1–0.3), moderate (0.3–0.5), large (0.5–0.7), very large (0.7–0.9), and nearly perfect (0.9–1.0). Comparisons between technical skills efficacy, weight of these determinants on total goals scored and final classification were executed by using one-way ANOVA, with significance value of $p \leqslant 0.05$. The Bonferroni procedure was applied as a multiple comparison between-group post-hoc test. All statistical analyses were performed with the IBM SPSS® Statistics (version 25, Chicago, USA) for the value of $p < 0.05$.

Ethical approval

The conducted research is not related to either human or animal use.

Results

As presented in Table 1, each team had an average (*SD*) of 20.8 (4.7) penalties and 42.8 (11.2) direct free-hits on the basis of the Portuguese senior rink hockey full-season analysis. Of the offensive penalties per team, a mean (*SD*) of 8.4 (2.5) were converted (40.3%). In addition, even with the medium effectiveness of this technical issue on the game, the mean (*SD*) weight of the converted penalties on total goals scored was 9.2% (3.3%).

Regarding another technical determinant of the game, offensive direct free-hits were more prevalent: mean (*SD*) of 42.8 (11.2) per team, full-season breakdown. Despite the higher prevalence of direct free-hits, the effectiveness of this parameter was lower than that of penalties (27.1%). In consequence, the mean (*SD*) weight of the converted direct free-hits on total goals scored was 12.9% (5.2%). Overall, both types of technical determinants described above had a significant weight (22.1%) on team performance, namely on total goals scored.

When applying the Pearson bivariate correlation between the effectiveness of direct free-hits and the final classification in the rink hockey first league, a consistent inverse relationship was observed, representing a very large correlation between both (r = –0.71 [–0.29; –0.9], p = 0.004). The same dimensions of inverse associations were observed among penalties' effectiveness and the final classifications, representing a large correlation between both (r = –0.58 [–0.07; –0.85], p = 0.029). This linear pattern is illustrated in Figure 1.

When the analysis was stratified by the proficiency level (Table 2), the teams that were in the champions' places (1st–4th) presented greater efficacy of direct free-hits and penalties, indicating means (*SD*) of 32.7 (2.8) and of 43.5 (3.7), respectively. In comparison, teams in CERS places (5th–9th) had means (*SD*) of 30.6 (6.1)

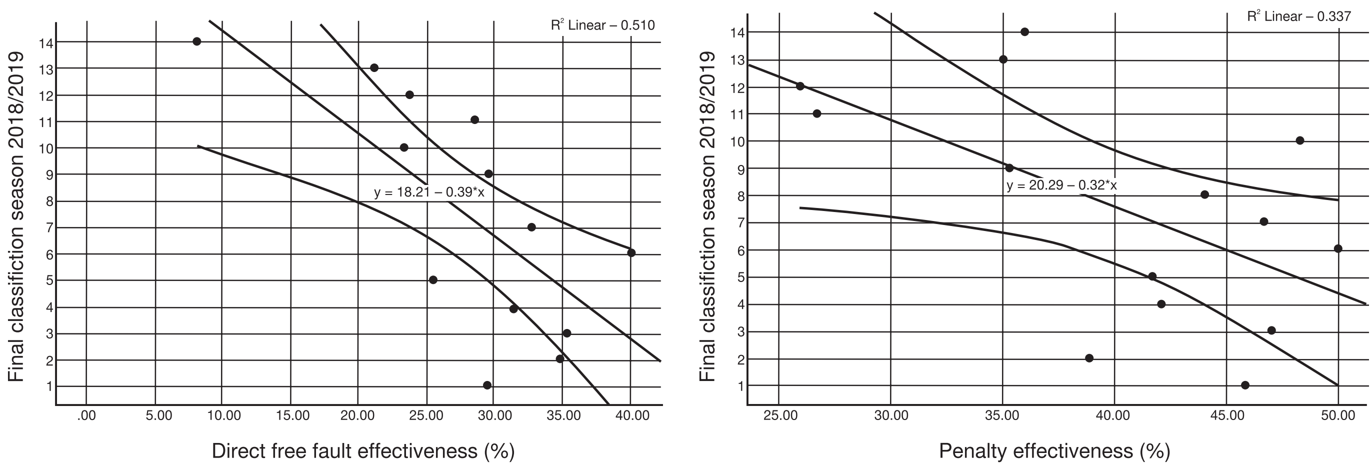

Figure 1. Relationship between the effectiveness of direct free-hits, penalties, and final classification in the championship

and 43.5 (5.6), respectively, and lower-rank teams (10th–14th) had means (*SD*) of 21.0 (7.7) and 34.4 (9.0), respectively. Despite their higher efficacy, the top 4 teams revealed significantly lower weights of converted direct free-hits and penalties on total goals scored in the league when compared with the other groups. The weights for this metric were as follows: 15.3% (1st–4th), 25.6% (5th–9th), 23.9% (10th–14th) ($p < 0.05$).

After applying the Bonferroni procedure, in multiple comparisons, consistent significant differences were found between groups 1 and 2 ($p = 0.006$) and groups 1 and 3 ($p = 0.020$) regarding the weight of direct free-hits and penalties on total goals scored.

As mentioned above, the effectiveness of these technical determinants is an important predictor of team performance that increases the positive balance between attack and defence. A clear linear relationship was observed between the ratio of goals scored and goals conceded with the final classification in the rink hockey championship (Figure 2). This ratio explains 83% of the variation in the final classification. In addition, Figure 2 illustrates a clear gap between the 5 teams above in the table and the other teams, with the 5 best teams in the final classification all presenting ratios between attack and defence of above 0.

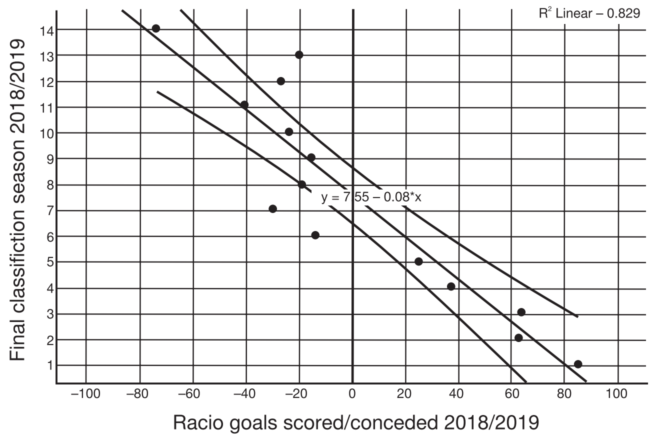

Figure 2. Relationship between the ratio of goals scored and goals conceded with final classification in the championship

Discussion

Rink hockey is characterized by consistent intermittent changes between phases/moments during the game, as is expected of any invasion sport. The different moments of a match lead to offensive actions that may result in a goal. Currently, the offensive phases or moments that characterize goals are marked by tactical complexity. The main findings of this study showed

Table 2. Technical determinants of efficacy and weight on total goals scored by category of final championship classification

Mean (*SD*)	Group 1*	Group 2**	Group 3***	*p*
Efficacy of direct free-hit (%)	32.7 (2.8)	30.6 (6.1)	21.0 (7.7)	0.030
Weight of converted direct free-hits on total goals scored (%)	8.8 (1.5)	16.0 (3.8)	13.1 (6.4)	0.106
Efficacy of penalties (%)	43.5 (3.7)	43.5 (5.6)	34.4 (9.0)	0.091
Weight of converted penalties on total goals scored (%)	6.5 (0.8)	9.6 (1.6)	10.8 (4.7)	0.137
Weight of converted direct free-hits and penalties on total goals scored (%)	15.3 (2.2)	25.6 (3.7)	23.9 (4.8)	0.005

* champions (1st–4th), ** CERS (Confédération Européenne de Roller Skating) (5th–9th), ***others (10th–14th)

that individual technical offensive determinants were consequences of tactical offensive actions, such as direct free-hits and penalties, and their effectiveness had a great impact on the final classification of the first league, accounting for at least 22.1% of the total goals scored. As expected, the higher classified teams exhibited higher scores of effectiveness in individual technical determinants. However, the weight of this efficacy on the total number of goals scored by each team was significantly higher on the below categories of the final classification.

Regarding the ratio of goals scored to those conceded and its linear relationship with the final classification, the top 5 teams presented a greater difference in relation to the other teams. In fact, winning teams in other team sport contexts – such as futsal [19] or handball [20] – presented greater offensive technical actions, as well as a higher ratio of goals scored to goals conceded, which resulted in better final outcomes (i.e., higher final classification) [21], which is in line with our results. This may be because the best teams generally have the best players and the best goalkeepers, as well as the best training conditions, which potentiates the balance between offensive and defensive determinants.

In rink hockey, in terms of total goals scored, direct free-hits were the most influential individual technical determinant. However, it was not as effective as total penalties in favour. These data indicate that despite being less frequent, penalties have a higher success rate in offensive terms than direct free-hits. In penalties, the goalkeepers, regarding technical issues, are more conditionate to have a global success; these are a difficult individual technical action to reproduce in training sessions. The precision and power of shots and the rule penalizing goalkeeper movements are some of the conditions that minimize exposure during training process.

Despite these differences in effectiveness, both technical determinants had an important role in the final classification. In line with the present results is a descriptive observational study of 3 games played by the Portuguese national futsal team, in which it was found that out of 56.9% of organized attacks that resulted in goals scored, 25.8% were from set pieces and only 17.4% were from counterattacks [21]. This indicates that set pieces have a great weight in the final result of a match and, therefore, in the final classification of a team. Also, in other team sport contexts (handball), it was observed that the shots from 6 m, 7 m, and 9 m were the most effective offensive actions [22].

Penalties and direct free-hits are very important in rink hockey, as they are 1 × 1 actions, with the remaining players at a considerable distance, which often gives the player who scores the set ball a second ball (i.e., another chance to score). Moreover, the greater effectiveness in scoring from penalties than from direct free-hits might be because the goalkeepers can only act from the moment the field player touches the ball. As penalties are executed closer to the goal than direct free-hits, the time that goalkeepers have to act is reduced, which may affect the final result. Also, the fact that the players start 1 × 1 actions (in the case of direct free-hits) gives goalkeepers the same probabilities as the field players. In addition, it makes the training process of direct free-hits more frequent, thereby improving the performance of both players involved in the technical action in contrast to the penalties exposure.

Considering the correlations of the efficacy of offensive direct free-hits and penalties with the final classification of the league, an inverse relationship was found between both situations, meaning that higher rankings depend on the effectiveness of offensive determinants. In fact, in a descriptive observational study that analysed 3 matches played by the Portuguese futsal national team in the European Selection Championship, set piece actions presented a higher rate of effectiveness (46.2%) than organized actions (15.4%) and counterattacks (38.5%) [21].

Research in the handball context demonstrated a high prevalence of goals scored from 7-m hits among senior winning teams [23]. Furthermore, it was documented that winning teams had greater 7-m hit effectiveness (around 79.5%) when compared with all other technical determinants, as well as in relation to losing teams [24]. Moreover, a clear gap was shown between winning teams and losing teams in terms of the effectiveness of offensive actions, which is in concordance with the results of the present study.

Despite these results, the top 4 teams were significantly more effective in scoring from direct free-hits and penalties than the other teams owing to the more proficient patterns of their athletes. In a study conducted during the 2013 World Handball Championship, the authors stratified teams into 3 groups by their rankings, as was done in the present study. They found that better teams had greater effectiveness in terms of total attempted shots in relation to their lower-ranked counterparts [25]. In another study that analysed performance determinants of Olympic, World, and European handball teams, it was observed that highly ranked European teams (among the top 8) had greater offensive actions efficiency than the other teams [26]. However, those offensive actions were related to offensive transitions and not set pieces. In addition, our study described that in rink hockey teams, these individual technical determinants were weighted more heavily in terms of total goals scored in low-ranked teams. This finding highlights the importance of achieving effectiveness and designing the season while preparing a specificity in the squad available.

As the effectiveness of offensive technical determinants is related to winning teams [7], it is expected that teams placed at the top of the classification depend relatively little on set pieces, as their style of play may result in better-organized attacks, transitions, and specific moments of recovering the ball, which result in goals. In contrast, other teams have significantly fewer opportunities, thus giving more weight to the individual situations that are available. Also, with regard to ball repossession and its natural offensive transition, which is typical of invasion games and of rink hockey in particular, it is more likely that a team will regain the ball in the defensive area of the field nearest to their goal [7]. Little is known about the types and direction patterns of shooting or the direct free-hit, and some studies were based on the previous rules, which placed different constraints on the actual game. However, recent research has revealed that direct free-hits in zone 3, with previous dribbling, converted by left-handed players are the most effective [12].

The present study has some limitations. We were unable to make indirect or direct observations of the games; however, we had access to the official game bulletins provided by the FPP, validated by the official referees. All data were collected and analysed by level II and III coaches. In addition, we performed a double check of the variables of interest by trained technicians; this showed an almost perfect reliability.

On the other hand, the use of retrospective data from all teams across a full season among senior athletes provides a representative sample size of some important determinants of rink hockey. As such, this study presents some practical applications. As the efficiency of set pieces has a great influence on the final classification, the bottom teams would benefit from more exposure to set pieces during training. Observations and analyses of opponents' defensive and offensive set pieces could also help these teams to improve their effectiveness. Moreover, coaches should use players who are more comfortable converting set pieces and are highly effective in doing so, thereby promoting a cross-sectional athlete specificity.

Conclusions

This study aimed to analyse the correlations between team performance and individual technical determinants of rink-hockey actions. Top teams, specially the top 5, clearly have higher ratios of goals scored to goals conceded than low-ranked teams, which demonstrates the importance of defensive/offensive balance. While offensive direct free-hits were the most prevalent parameter, penalties were the most effective technical determinant in terms of total goals scored. Both had a direct impact (above 20% of total goals scored) on the overall season performance – final classification. Despite the importance of the individual technical determinants, the success of the top 4 teams depended relatively little on set pieces because of their offensive style of play. Knowing what individual technical determinants are more closely related to strong team performance allows coaches to prioritize training sessions so that they can highlight their athletes' specializations.

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Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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SERVE EFFICIENCY DEVELOPMENT IN WOMEN'S VS. MEN'S PROFESSIONAL TENNIS

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ABSTRACT
Purpose. The purpose was to identify possible gender-specific differences in long-term serve efficiency development in professional women's and men's tennis.
Methods. The analyses focused on 2 approaches: (1) total tournament comparison and (2) 2nd tournament week vs. 1st tournament week comparison. The data include all single matches at the Wimbledon Championship between 2002 and 2015 (ladies: $n = 1771$, gentlemen: $n = 1772$).
Results. The findings showed significant development differences in favour of elite men over elite women in both comparisons. Regarding the total tournament comparison, men's development of 2nd serve points won ($p < 0.001$; $r = 0.86$), 1st serves in ($p < 0.05$; $r = 0.72$), and double fault ($p < 0.001$; r = 0.85) percentages improved significantly more. As per the 2nd tournament week vs. 1st tournament week comparison, men's development of 2nd serve points won ($p < 0.05$; $r = 0.68$) and double fault ($p < 0.01$; $r = 0.86$) percentages improved significantly more.
Conclusions. The study revealed serve efficiency development advantages for men over women in both comparisons, especially regarding the quality of the 2nd serve, whereas no development advantages in favour of women over men could be observed in any analysed parameter, indicating possible needs to adapt elite women's coaching.
Key words: elite, coaching, practice, gender, game opening, Wimbledon

Introduction

The importance of the serve in professional women's and men's tennis is well-known [1–4], with an even bigger impact on grass court at Wimbledon compared with the Australian, French and US Open [5–7]. Previous research offers distinguished scientific analyses on elite men's and women's tennis [1, 3–5, 7, 8–14]; however, just over a handful of them took gender-specific differences into account [6, 15–19]. Recently, long-term serve efficiency development has been reported across 14 years (2002–2015) of the Ladies and Gentlemen All England Championships at Wimbledon, stating advantages for players competing in the 2nd tournament week compared with players competing in the 1st tournament week; this is particularly prominent in men's tennis [8, 14]. Directly comparing women's with men's serve efficiency may offer valuable insights not only for players and coaches of both genders, but also for the scientific community. This is by raising the awareness of possible serve efficiency development advantages for women over men or vice versa and if so, players, coaches, and scientist could try to identify differences in the individual training methods. Earlier studies showed that elite men hit significantly more aces and won significantly more points while serving than elite women [17, 20–23]. On this basis, Verlinden et al. [23] speculated about the disparity in physical strength and stature, as well as serve speed as the reason of these gender differences of served aces [24]. Comparing the fastest known serves (Samuel Groth: 263 km/h, 2012; Sabine Lisicki:

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210.8 km/h, 2014) may underline the gender-specific biological disparities between men and women, giving men strategical advantages, since the serve is potentially the most dominant shot in modern tennis [25]. With respect to commonly accepted body constitutional differences [23, 26, 27], it may be considered misleading to interpersonally compare women's with men's serve efficiency. Cumulated by Elliott et al. [26], previous research suggests anthropometric and physiological differences referring to height (i.e., absolute size), muscular strength, flexibility, and power [28, 29], Moreover, and referring to movement learning and motor control, analogous movement patterns have been reported to be functionally improbable [30]. Thus, both physical and motor performance are well-reported to cause a gender-specific impact on serve performance, which has also been based on match-play data [26]. However, with the consideration of intrapersonal comparisons, analysing gender-specific serve efficiency development over time seems reasonable and purposeful, particularly with recently published long-term serve efficiency results of elite men and women [8, 14]. Bearing the above in mind, serve efficiency development in women compared with men competing in the 1st tournament week and 2nd tournament week may help understand gender-specific differences in successfully competing and eventually setting a match strategy as well as preparatory practice patterns.

Therefore, the present study aimed to analyse possible serve efficiency development differences in professional women's and men's tennis within the last 2 decades (Wimbledon 2002–2015; ladies' matches: n = 1771, gentlemen's matches: n = 1772) in order to specify possible gender-specific serve efficiency recommendations to enhance future practices. It was intended to generally identify gender-specific serve efficiency development differences within prominent serve-related parameters based on earlier research (e.g., service game, 1st serve and 2nd serve points won, aces, and double fault percentages) [8, 14]. Further, the awareness of development advantages in women's compared with men's tennis or vice versa may offer purposeful/valuable knowledge for players, coaches, and scientist, allowing to draw conclusions for their own practice patterns (e.g., increased focus on improving 2nd serve quality) or future research (e.g., survey of practice time and focus asking players and coaches of both genders).

Since the modern game of tennis has become less technique-based and increasingly more explosive and dynamic, the serve constitutes a key factor of success and significant tactical changes [25, 31].

Material and methods

Based on the results of 2 earlier studies by Grambow et al. [8, 14] which focused on long-term serve efficiency development in elite women's and men's tennis, as well as possible performance differences within world class tennis players by comparing data of players competing in the 1st tournament week with data of players competing in the 2nd tournament week of the All England Championships between 2002 and 2015, the present study involves 2 main gender-specific comparisons: (1) total tournament comparison and (2) 2nd tournament week vs. 1st tournament week comparison.

Data set

The total tournament data contain all matches played at Wimbledon between 2002 and 2015, specifically 1771 ladies' matches (service games: n = 37,717; serves: n = 248,135) and 1772 gentlemen's matches (service games: n = 63,838; serves: n = 401,527). In turn, 1st tournament week data contain 1562 ladies' matches (service games: n = 33,150; serves: n = 218,028) and 1563 gentlemen's matches (service games: n = 55,989; serves: n = 352,748), and 2nd tournament week data contain 209 ladies' matches (service games: n = 4567; serves: n = 30,107) and 209 gentlemen's matches (service games: n = 7849; serves: n = 48,779). The data were retrieved from the Wimbledon Information System (presented by IBM) in collaboration with Brain Game Tennis and with the approval of the German Sport University Ethics Committee.

Analyses

As explained earlier, body constitutional differences [23, 26, 27] seem to disqualify direct comparisons by absolute numbers; therefore, the gender-specific development over time referring to the individual starting level and improvement percentages should be investigated (i.e., intrapersonal comparison).

For the intrapersonal gender-specific total tournament comparison, yearly women's and men's data were merged in 2-year groups (2002 + 2003, 2004 + 2005, et seq.) for each of the 8 analysed serve parameters to minimize potential statistical peaks. The observed development over the course of the 7 combined tournament year groups (starting with 2002 + 2003 until 2014 + 2015) for both the women's and men's data was compared to identify gender-specific differences, by analysing mean values of the following years, with the 2002 + 2003 value serving as baseline, and looking for the possible intrapersonal gender-specific differences.

Contrary to this, the intrapersonal gender-specific 2nd tournament week vs. 1st tournament week comparison involved development differences within each 2-year group for the respective world class cohort.

Following the research methodology of Grambow et al. [8, 14], the analysed serve parameters listed below, which are commonly known as valid measures for serve efficiency [32, 33], were applied, with only one parameter added (i.e., 1st serve in):

– the number of 1st and 2nd serve points won by each player (i.e., serve success);

– the number of service games won by each player (i.e., serve success);

– the number of 1st serves in served by each player (i.e., serve performance);

– the number of double faults served by each player (i.e., serve performance);

– the number of aces served by each player (i.e., serve performance);

– the number of serve and volley points played by each player (i.e., serve strategy);

– the number of serve and volley points won by each player (i.e., serve strategy).

The 8 recorded serve efficiency parameters were categorized and divided into 3 groups, again following the methodology of Grambow et al. [8, 14]. The percentages for 2nd serve points won, 1st serve points won, and service games won were assigned to the category *serve success*, since these parameters display how successful men and women were against their opponents while serving. The percentages for valid 1st serves, double faults, and aces were assigned to the category *serve performance*, since these parameters are only influenced by the players' own performance, without their opponents playing any shot. The percentages for serve and volley points played and serve and volley points won were assigned to the third category, *serve strategy*.

Statistical procedures

The statistical procedures were performed by using SPSS Statistics for Macintosh, version 27.0 (IBM Corp., Armonk, NY, USA), as well as Excel 2016 (Microsoft Corp., Redmond, WA, USA).

After *t*-tests application for predefined parameters in both comparisons, effect sizes were calculated by using Pearson's correlation coefficient and interpreted as small ($r \geq 0.1$), medium ($r \geq 0.3$), and large ($r \geq 0.5$) [34], more recently augmented as very large ($r \geq 0.7$) and extremely large ($r \geq 0.9$) [35].

Mean (*M*) and standard deviation (*SD*) are presented as percentages in Tables 1 and 2. The level of significance was set at $p < 0.05$ and, if applicable, further at $p < 0.01$ and $p < 0.001$.

Tables 1 and 2 present the minimum (^{min}) and maximum (^{max}) marks for the relevant percentages, which may be of value for coaches as benchmarks during practice with their athletes.

Ethical approval

The conducted research is not related to either human or animal use.

Results

Serve success

Following the intrapersonal gender-specific total tournament comparison over time, the analyses for 2nd serve points won showed significant development advantages for men's (M = 1.04; SD = 0.01) compared with women's (M = 1.01; SD = 0.10) percentages ($p < 0.001$; r = 0.86) (Table 1). The analyses for 1st serve points won revealed no significant development differences when comparing men's (M = 1.02; SD = 0.01) and women's (M = 1.01; SD = 0.01) percentages (p = 0.29), as well as when comparing service games won (men: M = 1.04, SD = 0.01; women: M = 1.03, SD = 0.15) percentages (p = 0.05) (Table 1).

Following the intrapersonal gender-specific 2nd tournament week vs. 1st tournament week comparison for 2nd serve points won, the analyses showed significant development advantages for men's (M = 1.04; SD = 0.28) compared with women's (M = 0.99; SD = 0.02) percentages ($p < 0.05$; r = 0.68) (Table 2, Figure 1). The analyses for 1st serve points won revealed no significant development differences when comparing men's (M = 1.03; SD = 0.02) and women's (M = 1.03; SD = 0.03) 2nd tournament week and 1st tournament week percentages (p = 0.86), as well as when comparing service games won (men: M = 1.04, SD = 0.28; women: M = 1.03, SD = 0.05) percentages (p = 0.61) (Table 2, Figure 1).

Serve performance

Following the intrapersonal gender-specific total tournament comparison over time, the analyses for 1st serves in showed significant development advantages for men's (M = 1.05; SD = 0.01) compared with

Table 1. Total tournament parameter percentages including minimum and maximum benchmarks

Total tournament parameters			Tournament years						
			2002 + 2003	2004 + 2005	2006 + 2007	2008 + 2009	2010 + 2011	2012 + 2013	2014 + 2015
Serve success	2^{nd} serve points won (%)	Ladies	45.53	45.45^{min}	46.18	45.95	46.85^{max}	46.33	46.09
		Gentlemen	50.05^{min}	51.62	52.13	52.10	51.70	52.23	52.70^{max}
	1^{st} serve points won (%)	Ladies	64.63	64.70	64.61^{min}	64.97	65.84	64.90	66.18^{max}
		Gentlemen	72.94^{min}	73.53	72.99	74.63	74.39	73.98	74.76^{max}
	Service games won (%)	Ladies	67.18^{min}	67.51	68.55	68.36	70.46^{max}	68.89	69.56
		Gentlemen	79.76^{min}	82.18	82.44	83.09	83.09	83.31	84.40^{max}
Serve performance	1^{st} serve in (%)	Ladies	61.30^{min}	62.91	63.81^{max}	63.05	63.60	63.39	63.17
		Gentlemen	60.18^{min}	62.32	63.50	62.28	63.61	63.89^{max}	63.62
	Double faults (%)	Ladies	5.43^{min}	5.13	4.76	5.02	4.70	4.53^{max}	4.59
		Gentlemen	4.74^{min}	3.96	3.22	3.48	3.26	3.04^{max}	3.41
	Aces (%)	Ladies	3.73^{min}	3.92	4.01	3.93	4.85	4.30	4.94^{max}
		Gentlemen	8.46^{min}	9.05	8.71	9.50	10.30	9.77	10.74^{max}
Serve strategy	Serve and volley points played (%)	Ladies	4.74^{max}	4.20	2.80	2.17	1.61	1.19	1.10^{min}
		Gentlemen	28.66^{max}	20.54	13.26	9.77	6.93^{min}	7.06	9.18
	Serve and volley points won (%)	Ladies	64.39	66.19	65.78	65.65	61.64^{min}	63.64	69.74^{max}
		Gentlemen	67.06^{min}	67.54	67.40	68.17	67.90	67.71	70.59^{max}

Table 2. Second tournament week parameter percentages including minimum and maximum benchmarks

Second tournament week parameters			Tournament years						
			2002 + 2003	2004 + 2005	2006 + 2007	2008 + 2009	2010 + 2011	2012 + 2013	2014 + 2015
Serve success	2^{nd} serve points won (%)	Ladies	45.01	46.45	44.89	47.30^{max}	46.73	43.84^{min}	46.89
		Gentlemen	50.80^{min}	53.00	53.37	54.40	55.74^{max}	52.29	54.23
	1^{st} serve points won (%)	Ladies	66.94	65.36^{min}	66.01	69.39^{max}	67.36	65.98	67.19
		Gentlemen	73.56^{min}	73.87	74.29	77.64	78.28^{max}	74.12	76.95
	Service games won (%)	Ladies	69.19^{min}	71.17	69.26	75.34^{max}	71.96	69.59	72.08
		Gentlemen	80.82^{min}	82.83	83.83	88.10	88.85^{max}	85.13	87.73
Serve performance	1^{st} serve in (%)	Ladies	62.98	64.48	62.20^{min}	62.35	63.56	64.81^{max}	63.45
		Gentlemen	59.81^{min}	60.86	63.43	63.13	64.14	64.42	64.74^{max}
	Double faults (%)	Ladies	4.83	4.62	5.18	4.97	5.27^{min}	4.20^{max}	4.41
		Gentlemen	3.75^{min}	3.32	2.64	2.87	2.81	2.38^{max}	2.64
	Aces (%)	Ladies	4.39^{min}	4.82	4.82	6.45^{max}	5.88	5.58	5.20
		Gentlemen	8.36^{min}	9.24	8.75	11.91	12.57^{max}	9.67	12.34
Serve strategy	Serve and volley points played (%)	Ladies	1.89	3.61	6.00^{max}	1.78	0.31^{min}	1.75	1.01
		Gentlemen	33.44^{max}	18.91	10.30	10.71	8.45	6.76^{min}	9.17
	Serve and volley points won (%)	Ladies	69.19^{min}	71.17	69.26	75.34^{max}	71.96	69.59	72.08
		Gentlemen	67.55	65.21^{min}	68.75	69.89	67.97	70.96	74.15^{max}

Figure 1. Intrapersonal gender comparisons of the 2nd tournament week vs. 1st tournament week's delta over 2 sequenced years from 2002 + 2003 to eventually 2014 + 2015 in different serve efficiency parameters for men (blue line) and women (orange line), including dotted trend lines, respectively

women's (M = 1.03; SD = 0.01) percentages (p < 0.05; r = 0.72) (Table 1). The analyses for double faults revealed significant development advantages for men's (M = 0.72; SD = 0.07) compared with women's (M = 0.88; SD = 0.04) percentages (p < 0.001; r = 0.85) (Table 1). The analyses for aces determined no significant development differences when comparing men's (M = 1.14; SD = 0.09) and women's (M = 1.16; SD = 0.12) percentages (p = 0.79) (Table 1).

Following the intrapersonal gender-specific 2nd tournament week vs. 1st tournament week comparison for 1st serves in, the analyses showed no significant development advantages for men's (M = 1.00; SD = 0.02) compared with women's (M = 0.99; SD = 0.24) percentages (p = 0.72) (Table 2, Figure 1). The analyses for double faults revealed significant development advantages for men's (M = 0.79; SD = 0.03) compared with women's (M = 1.02; SD = 0.11) percentages (p < 0.01; r = 0.86) when comparing the 2nd tournament week data vs. the 1st tournament week data (Table 2, Figure 1). The analyses for aces determined no significant development differences when comparing men's (M = 1.10; SD = 0.14) and women's (M = 1.24; SD = 0.31) percentages (p = 0.30) (Table 2, Figure 1).

Serve strategy

Following the intrapersonal gender-specific total tournament comparison over time, the analyses for serve and volley points played (p = 0.96) and serve and volley points won (p = 0.58) showed no significant development differences when comparing men's (played: M = 1.02, SD = 0.18; won: M = 0.39, SD = 0.18) and women's (played: M = 1.02, SD = 0.04; won: M = 0.46, SD = 0.25) percentages (Table 1).

Following the intrapersonal gender-specific 2nd tournament week vs. 1st tournament week comparison for serve and volley points played (p = 0.70) and serve and volley points won (p = 0.86), the analyses revealed no significant development differences when comparing men's (played: M = 1.02, SD = 0.03; won: M = 1.03, SD = 0.17) and women's (played: M = 1.04, SD = 0.15; won: M = 1.08, SD = 0.81) percentages (Table 2, Figure 1).

Discussion

Following earlier longitudinal research on women's and men's serve efficiency development at Wimbledon [8, 14], the present study aimed to find gender-specific differences regarding the individual development during the analysed period by using 2 different approaches to be able to directly compare women's and men's development. The findings of the intrapersonal gender-specific total tournament comparison over time showed significant advantages in favour of men's development in serve success (2nd serve points won percentages) and serve performance (1st serve in and double fault percentages) parameters. In the analysis of the intrapersonal gender-specific development differences of the 2nd tournament week vs. 1st tournament week comparison, again the same parameters (i.e. serve success: 2nd serve points won percentages; serve performance: double fault percentages) revealed significant advantages in favour of men's serve efficiency development.

On the basis of the results of earlier studies, increased serve efficiency for elite women's and men's tennis is well accepted [1–4, 6, 8, 9, 13, 14, 36], which ultimately leads to the question if there are differences regarding the elements and extent of the development between women and men.

Development is driven by competition and its impact on winning, which results in an increasingly more dynamic and faster paced while less technique-based modern game of tennis, characterized by strength, speed, and power; this makes the serve a key factor to strategic advantages and, by this, to winning [25, 31]. With the consideration of commonly accepted body constitutional differences [23, 26, 27] and the above indicated role of the serve in tactics and winning in tennis, increased serve efficiency parameters may be of more importance in elite men's tennis compared with elite women's tennis.

Total tournament data for men and women over time depict a general increase, as reported earlier [8, 14], but the intrapersonal gender-specific total tournament comparison shows significant advantages for men over women in 3 out of the 8 analysed serve efficiency parameters (i.e., 1st serve in, 2nd serve points won, and double fault percentages), with no parameters in favour of women over men. Men's development of 1st serve in percentages was significantly more efficient (p < 0.05; r = 0.72) compared with women's 1st serve in percentages, reasonably based on the lower starting level (men: 60.18%, women: 61.13%) in the combined Wimbledon tournaments of 2002 + 2003, since both men and women serve at around 63% of their 1st serves in over the following years with very close peak values (e.g. men: 63.89% in 2012 + 2013; women: 63.81% in 2006 + 2007). These percentages in both men and women confirm the previously reported 1st serve in percentages being around 60% [16, 24, 37], but at the same time show an increasing development, with a significant development advantage in favour of elite men.

Men's development of 2nd serve points won ($p < 0.001$; $r = 0.86$) and double fault ($p < 0.001$; $r = 0.85$) percentages, both being significantly more improved than women's development, seems even more impressive if one considers that men's starting level in both categories was already on a much higher level in the merged 2002 + 2003 Wimbledon percentages (e.g. 2nd serve points won: men: 50.05%, women: 45.53%; double faults: men: 4.74%, women: 5.43%). While men won their points following a 2nd serve at around 52% in the following years (peak value: 52.7% in 2014 + 2015), women increased to around 46% (peak value: 46.85% in 2010 + 2011). The mean value of the 2nd serve points won development difference in elite men's tennis ($M = 1.04$) presents an advantage compared with elite women's tennis ($M = 1.01$). Bearing in mind that all analysed matches were Main Draw Singles matches at Wimbledon, which relates to high performance elite tennis, an increase of 4% appears to be very impressive, even more so when this increase is 4 times as big as the 1% in women's tennis over the same time. Simultaneously, another plausible interpretation of these statistical numbers could be found in the women's return performance. The winning percentages of service points, especially for 2nd serves, are influenced by the return quality of the opponent. With this line of thought, an increased return performance in elite women's tennis (compared with a possibly less increased men's return performance) may cause the differences. Since the following double fault percentages, where again significant differences in favour of elite men were observed, obviously have a direct impact on the 2nd serve points won percentages – because every double fault is a lost point following a 2nd serve – a development advantage in favour of both men's categories seems more reliable. Double fault percentages decreased in both women's and men's tennis, but significantly more in men's tennis. While women served their weakest percentage of 5.43% compared with 4.74% among men (both in the merged 2002 + 2003 events), women managed to decrease to 4.53% (2012 + 2013) and men managed to decrease to 3.04% (2012 + 2013). Men's percentages are between 3.04% and 3.48% over the last 10 years, while women's percentages are between 4.53% and 5.02% in the same time. The difference of development in this area raises questions regarding the importance of practising 2nd serves, underlining earlier findings of 2nd serve winning percentages in elite women's tennis [15]. Previous research has shown that the serve has an even bigger impact in elite men's tennis [20, 38], but if one considers speed differences, not least due to body constitutional differences, and the individual starting level (e.g. men: 4.74%, women: 5.43%), it seems plausible to ask for a similar development possibility over such a long time. Nevertheless, men's (double fault) percentages improved significantly more, which leads to the conclusion that women's tennis may increase the amount of time and/or the way of practising 2nd serves.

The findings regarding development differences in the intrapersonal gender-specific 2nd tournament vs. 1st tournament week comparison showed advantages in the same categories. As in the total tournament comparison, men's development improved significantly more in 2nd serve points won percentages ($p < 0.05$; $r = 0.68$) and in double fault percentages ($p < 0.01$; $r = 0.86$) compared with women's development.

Preventing any misleading interpretation, it should be stated that men and women competing in the 2nd tournament week perform at higher percentages across all analysed categories compared with players competing in the 1st tournament week, as earlier evidence has shown [8, 14]. Men and women improved their 2nd tournament week percentages over time across all categories, but like in the gender-specific total tournament comparison, advantages in the development can be proven statistically in favour of men over women in 2nd serve points won and double fault percentages. Adding to these findings and although only descriptive, Figure 1 illustrates and directly compares men's and women's serve efficiency parameters, showing the percentages and the trend lines for these percentages. Especially noticeable are the differences between men's and women's trend lines, presenting improvement for men's 2nd tournament week data compared with men's 1st tournament week data in all 6 categories of serve success and serve performance; over the same time, the trend for women's 2nd tournament week data compared with 1st tournament week data slightly decreased. This does not mean that women's percentages in the 2nd tournament week are decreasing; the slightly decreasing trend lines rather seem to origin in 1st tournament week improvements. This adds to former research implying that an extended world class cohort in women's tennis [14], and at the same time men competing in the 2nd tournament week, maintained and increased their advantages.

The findings of both intrapersonal gender-specific comparisons revealed no statistically relevant development differences in favour of women over men or vice versa for the two serve strategy parameters (e.g. serve and volley points played percentages and serve and volley points won percentages). Even if any advantages or disadvantages, especially in the 2nd tournament week vs. 1st tournament week approach, had been observed, they would have to be considered with care, since the serve and volley percentages of women competing in the 2nd tournament week were close to zero.

The findings of both intrapersonal gender-specific comparisons showed no development advantages at all in favour of women over men in any of the analysed parameters. This adds to previous research by Brown and O'Donoghue [20], who analysed similar parameters and reported significantly greater 1st and 2nd serve winning percentages for men over women, who were also serving higher ace and fewer double fault percentages. These percentages relate to matches of all 4 Grand Slam tournaments in 2007. If one considers the long-term approach and the number of categories analysed while comparing the intrapersonal serve efficiency development differences of the respective world class in women's and men's tennis, finding no development advantages at all in favour of women may be seen as a surprise. Previous research comparing elite women's and men's tennis showed mostly advantages on either side [15, 17, 19] or in favour of elite men, but these findings were related to shorter periods of observation [6, 24].

Limitations

In science, prospective trials should be used rather than retrospective analyses, which is not feasible when investigating professional tennis at the highest international levels of competition, especially when analysing long-term data over a period of 14 years.

Using data of pre-set categories (i.e., presented by IBM) may be considered limiting itself, since official category definitions are most reasonable but ultimately non-verifiable pre-set definitions; moreover, they are delivered by a third party. This remains true even if the company is well-established and the data presented are used as official and commonly well-accepted data (e.g. media coverage, coaching).

Big data analyses have tendencies to present significant results because of the large amount of data, which raises the problem of translating these results to the actual practical impact. Effect sizes were calculated to minimize this risk and weigh in the presented significances.

The comparability of the collected findings may be limited in certain areas, since the gender-specific development differences were analysed exclusively for elite men's and women's tennis competition on grass court. This should be taken into consideration when comparing the findings with e.g. hard court or clay court tournaments, lower level competitions, or boys and girls performance.

The data set did not present any biological parameters, such as size/height, weight, or playing hand of the players, so all performed analyses could not account for possible differences in these areas.

Finally, the risk of statistical bias exists, since findings regarding serve success, serve performance, or serve strategy may be influenced by medical issues if the players starting or resuming match-play are not in their best health condition. However, given the enormous number of total matches (e.g. men: 59 injury retirements / 1772 total matches; women: 24 injury retirements / 1771 total matches), the potential data interference may be considered as minor to none.

Conclusions

The aim of the present study was to directly compare long-term serve efficiency development in elite women's and men's professional tennis in order to identify possible advantages for women or men. Therefore, the study based its comparative approach on earlier research, which focused on the Ladies' and, respectively, Gentlemen's Wimbledon Championships held between 2002 and 2015. Furthermore, at some point, most coaches work not only with female or male athletes exclusively, so a better understanding of gender-specific serve efficiency benchmarks (descriptive) may be of general interest, particularly for coaches.

The findings imply significant advantages for elite men's development over elite women's development regarding serve success and serve performance parameters for the intrapersonal gender-specific total tournament comparison over time: in detail, 2nd serve points won percentages, double fault percentages, and 1st serve in percentages. The findings of the intrapersonal gender-specific 2nd tournament week vs. 1st tournament week comparison also depict significant development advantages for elite men over elite women for 2nd serve points won percentages and double fault percentages. The findings for intrapersonal gender-specific 2nd tournament week vs. 1st tournament week comparison additionally suggest an increasing development in all 6 serve success and serve performance parameters in favour of men competing in the 2nd tournament week (last 16 of the world cohort) over men competing in the 1st tournament week (extended world class cohort), whereas the opposite development is suggested for elite women's tennis since the trend lines for all

6 serve success and serve performance parameters are decreasing, which means that the extended world class cohort (women competing in the 1st tournament week) closes the serve efficiency gap to the women competing in the 2nd tournament week (last 16 of the world cohort). For both intrapersonal approaches, the gender-specific total tournament comparison over time and the gender-specific 2nd tournament week vs. 1st tournament week comparison, the serve strategy parameters (i.e. serve and volley points played and won percentages) showed no significant findings.

Conclusively, no development advantages were observed at all in any of the analysed serve efficiency parameters for women over men, while the results for 2nd serve points won, double fault, and 1st serve in percentages prove significant development advantages in favour of men over women. Adding the higher starting level at the 2nd serve points won and double fault percentages in men, it seems plausible to suggest an increase of training time or a change of training style regarding practice patterns of 2nd serves in elite women's professional tennis, and taking up earlier suggestions by Grambow et al. [14] regarding coaching implications in elite women's tennis, particularly the 1st and 2nd serve drill, as well as the serve target zone drill. Percentages shown in Tables 1 and 2 can be used as benchmarks.

Development differences may be driven by the importance of the (analysed) parameters for the strategy and, by this, the success of players, which leads to a conclusion that serve efficiency parameters may have an even bigger impact on strategic advantages and thus on the chances of winning in general in elite men's tennis compared with elite women's tennis.

In this context, future research may focus on scientific surveys directly interviewing professional tennis players and coaches to identify possible gender-specific differences regarding e.g. the actual amount of practice time put into training contents, such as practising 2nd serves, the importance women and men (players and coaches) ascribe to certain training contents, and the possibly different ways of practising serve efficiency related training contents. Future research may also focus on different surfaces, as well as junior tennis to succeed in tomorrow's tennis practice and, eventually, competition.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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DEVELOPMENT AND APPLICATION OF AN ELECTRICAL BUZZ WIRE TO EVALUATE EYE-HAND COORDINATION AND OBJECT CONTROL SKILL IN CHILDREN: A FEASIBILITY STUDY

original paper
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ABSTRACT
Purpose. There are many instruments to test children's motor coordination, but the problem is that none of them evaluates accuracy and precision during motor tasks. Therefore, the aim of the study was to develop and test the applicability of electrical buzz wire (EBW) as an instrument for assessing eye-hand coordination and object control skill in children, as well as to delimit the mean time and errors in tasks involving speed and/or accuracy.
Methods. The cross-sectional study involved 66 children (28 boys and 38 girls) aged 7–12 years. The variables evaluated were anthropometrics, hand dominance, and Movement Assessment Battery for Children (MABC-2). The outcomes were time (s) and error (*n*) during 4 tasks while changing speed and wire loop size.
Results. The ANOVA analysis showed statistically significant differences in the time variable [F(4, 502) = 8.6155, $p < 0.001$] and in the error [F(6, 502) = 69.209, $p < 0.001$]. The mean values of time and errors in each task were standardized after linear regression: 2.38 errors and 37 seconds in task 1; 3.2 errors and 35 seconds in task 2; 6.4 errors and 24 seconds in task 3; and 6.4 errors and 23.1 seconds in task 4. The error and time variables in EBW presented weak negative correlations with all MABC-2 domains.
Conclusions. EBW was developed; the time and errors with a comfortable speed were lower than with a high speed, regardless of the difficulty level. Time and error values were also standardized in this age group.
Key words: children, eye-hand coordination, motor skill, health evaluation, task performance, functional performance

Introduction

The evaluation of motor coordination in children is important to identify delays in motor development [1], treatment evolution [2], performance between genders [3], physical fitness [4, 5]. So, it can be useful in different settings: clinical, sports and physical education classes. Applying instruments and scales that contain playful and challenging principles is therefore an interesting approach. There are many instruments to test children's motor coordination, but there is no gold standard, especially to evaluate eye-hand coordination and object control skill [6]. Most of these instruments focus on identifying children with fundamental movement skill development disorders and are rather time-consuming [7].

The ludic principle can be mainly employed to assess the eye-hand coordination and object control skill in children. In this way, an electrical buzz wire (EBW) was built as an attractive therapeutic tool. Some authors have demonstrated the use of EBW to assess children's facial expression during errors [8], manual dexterity training [9], and attentional and neuropsychiatric deficits [10], but none investigated the accuracy and precision during eye-hand coordination and object control skill assessment in children.

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EBW is considered an easy-to-reproduce, low-cost, and ludic instrument. So, can it be used as an evaluation tool for eye-hand coordination, focusing on the accuracy and precision when performing the activity? There is one study involving eye-hand coordination and object control skill in adults based on children's toys [11], but none has applied EBW to assess object control skill in children, and there are no parameters of the task protocol in this population.

A child needs to develop a great motor repertoire, especially for tasks that require reach and hand grip [12]. These patterns can change and self-organize depending on different environments [13, 14]. The use of EBW allows an interaction between reach and grip in several trajectories and challenges, and the child constantly needs to adapt the movement patterns of the upper limb, as well as the task speed. In addition, the instrument provides visual and auditory cues that require more attention during the performance. The use of EBW may reflect motor skills that the child performs in their usual environment.

On the basis of this background, we highlighted the relevance of testing eye-hand coordination and object control skill by using an instrument with a high level of practical feasibility. Therefore, the aim of the study was to develop and test the applicability of EBW as an instrument for assessing eye-hand coordination and object control skill in children, as well as to delimit the mean time and errors in tasks involving speed and/or accuracy. The hypotheses of this study were as follows: (1) EMW allows to evaluate the accuracy and precision of object control skill; (2) tasks involving higher speed decrease the time and increase errors; (3) tasks involving higher accuracy increase the time and decrease errors.

Material and methods

Study design, setting, and participants

This was a cross-sectional study with a convenience sample of 66 children (28 boys and 38 girls) aged 7–12 years, of both sexes, and regularly enrolled at school. The children were recruited at a public school of Uberaba (Minas Gerais, Brazil) between March 2018 and July 2019.

Eligibility criteria

The inclusion criteria involved: absence of motor, neurological, or cognitive impairments, age 7–12 years, standard score ≥ 8 in the Movement Assessment Battery for Children (MABC-2), and no use of any prescription medications. We excluded children who did not conclude the tests at any moment.

Data collection setting

The collections were carried out in the school environment, in a reserved room, without noise, during a break from classes. Two independent observers accompanied the collections. There was a warm-up period with EBW (1 minute of EBW free exploration was allowed).

Data sources and measurement

Anthropometric variables

Body mass was measured with digital scales (Filizola®), and height with a stadiometer (Welmy®). Body mass index (BMI) was calculated in accordance with the Quetelet equation (BMI = body mass / height^2) by using body mass measured in kilograms and height measured in meters. Upper arm length was determined on the left side of the subject.

Lateral dominance

The Harris test of lateral dominance was used to establish each child's dominant hand. The test appears to be the one most often used in research studies determining lateral dominance. It is easily administered and usually turns out enjoyable to the subjects. The Harris test is validated for children and the reliability for the 4 hand dominance tasks equals 0.89 [15].

The Movement Assessment Battery for Children, 2nd edition

This test is used to identify motor disorders in children aged 3–16 years [16]. The MABC-2 protocol consists of manual dexterity, aim and catch, and static and dynamic balancing tests. It was applied just one time, in accordance with the instrument recommendation. The score ranges from 1 to 19 for each item, and for each value, there is a corresponding percentage, which can range from 0.1% to 99.9% [17]. A score equal to or smaller than the 5th percentile or 8 standard score is the cut-off point for motor difficulties in coordination [18]. The MABC-2 used in this research was original and complete, and was provided by the Federal University of São Carlos. The internal consistency for MABC-2 equalled α = 0.90. The test-retest reliability for the total score was excellent, with an intraclass correlation coefficient of 0.97 in children [19, 20].

Buzz wire coordination test

An EBW coordination evaluation system was developed by researchers from the Biomechanics and Motor Control Laboratory of Federal University of Triângulo Mineiro, on the basis of children's toys and the instrument proposed by Read et al. [11]. The device measurements are specified in Figure 1. As can be observed in Figure 2, one must guide a wire loop around a complicated wire track without touching the loop to the track, using binocular vision. A buzzing noise indicates whenever contact is made.

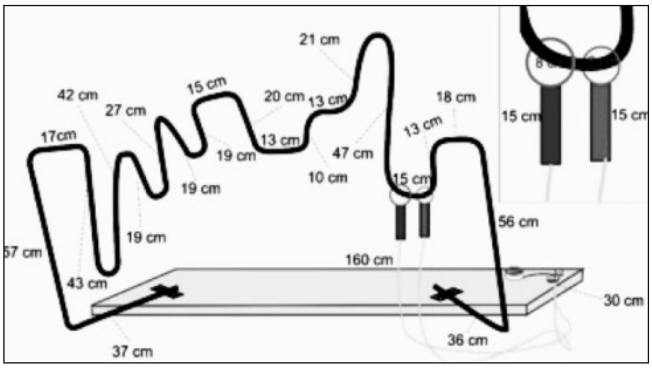

Figure 1. Electrical buzz wire

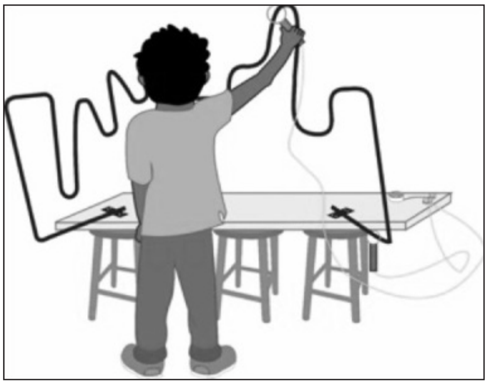

Figure 2. Illustration of a child executing the task

The buzzing noises indicated errors and they were registered by 2 independent evaluators. The task time was recorded with a stopwatch (Akso®). All tasks followed the commands presented in Table 1.

Four tasks were performed with 2 commands and 2 wire loop sizes (Table 1). Five trials were conducted in each task. A 1-minute rest was applied between the trials. For data analysis, the first trial was eliminated and the mean values of error and time of the other trials were considered.

The index of task difficulty was proposed by Fitts's law [21]:

$$t = a + b \cdot \log2 (d/w)$$

where t – index of difficulty, a – fixes cost portion, b – control rate, d – distance from the starting point to EBW, and w – width of the wire loop. In tasks 1 and 3, the index of difficulty was 1.34, and in tasks 2 and 4, the index was 1.42.

Sample size

The sample size calculation involved the moderate correlation coefficient (r = –0.4) between EBW time and error and MABC-2 scale considering the statistical significance of 0.05 (95%), type II error of 0.1 (90%), and effect size of 0.63. The sample size was calculated by using the PASS 13 application. The minimum sample size for this study was 61 children.

Statistical analysis

Descriptive statistics were used to describe the characteristics of the participants. Mean and standard deviation values were reported for continuous variables, and number and percent were provided for categorical variables. The Shapiro-Wilk test was performed to verify the normality of the data. One-way ANOVA was applied for error and time variables in EBW, and post-hoc Tukey's test for multiple comparisons between the tasks. Linear regression was used to establish the relationship between error and time during each task.

Table 1. Tasks and commands during the electrical buzz wire test

Task	Wire loop	Command
1	8.0 cm	Do the test in a comfortable speed, as accurately as possible. Try not to touch the ring in the buzz wire
2	6.0 cm	Do the test in a comfortable speed, as accurately as possible. Try not to touch the ring in the buzz wire
3	8.0 cm	Do the test as fast and accurately as possible. Try not to touch the ring in the buzz wire
4	6.0 cm	Do the test as fast and accurately as possible. Try not to touch the ring in the buzz wire

Spearman's correlation served to verify the associations between error and time variables in EBW and MABC-2 (total and domain scores). The inter-rater reliability was determined by Cohen's kappa coefficient (κ). Statistical significance of the results was accepted at $p < 0.05$. All data were analysed with the IBM SPSS Statistics for Windows (version 23.0; IBM Corp., Armonk, NY, USA).

Ethical approval

The research related to human use has complied with all the relevant national regulations and institutional policies, has followed the tenets of the Declaration of Helsinki, and has been approved by the Human Research Ethics Committee of the Federal University of Triângulo Mineiro.

Informed consent

Informed consent has been obtained from the parents of all individuals included in this study.

Results

Table 2. Demographic variables and task performance in the sample (n = 66)

Parameters	Average	*SD*
Age (years)	9.50	1.721
Sex (male:female)	28:38	
Lateral dominance (right:left)	56:10	
Body mass index (kg/m^2)	17.67	4.438
Upper arm length (cm)	54.70	2.997
Task 1		
Time (s)	33.70	4.307
Errors (number of buzzing noises)	2.52	1.850
Task 2		
Time (s)	35.05	5.290
Errors (number of buzzing noises)	2.31	1.870
Task 3		
Time (s)	24.02	4.560
Errors (number of buzzing noises)	6.45	2.359
Task 4		
Time (s)	23.11	4.202
Errors (number of buzzing noises)	6.45	2.818

The demographic variables and performance in the EBW tasks are shown in Table 2. The inter-rater reliability was 0.86 for error and 0.67 for time.

The ANOVA analysis revealed a statistically significant difference in the time variable [$F(4, 502) = 8.6155$, $p < 0.001$] and in the number of errors [$F(6, 502) = 69.209$, $p < 0.001$]. The post-hoc analysis demonstrated that the mean time in task 1 (*wire loop with 8 cm and low speed*) was statistically significantly different when compared with the mean time in task 3 (*wire loop with 8 cm and high speed*) (mean difference [MD]: 10.3; CI: –11.72 to –7.557; $p < 0.0001$) and task 4 (*wire loop with 6 cm and high speed*) (MD: 12.2; CI: –12.65 to –8.497; $p < 0.0001$). A statistically significant difference was observed between the mean time in task 2 (*wire loop with 6 cm and low speed*) and that in task 3 (MD: 8.8; CI: 9.042 to 13.2; $p < 0.0001$) and task 4 (MD: 10.7; CI: 9.982 to 14.14; $p < 0.0001$). In the error variable, it was noted that the mean error in task 1 showed a statistically significant difference when compared with the mean error in task 3 (MD: –5.1; CI: –4.921 to –2.898; $p < 0.0001$) and task 4 (MD: –5.4; CI: –4.951 to –2.928; $p < 0.0001$). The mean error in task 2 presented a statistically significant difference when compared with the mean error in task 3 (MD: –5.6; CI: –5.133 to –3.11; $p < 0.0001$) and task 4 (MD: –5.8; CI: –5.163 to –3.14; $p < 0.0001$) (Figure 3).

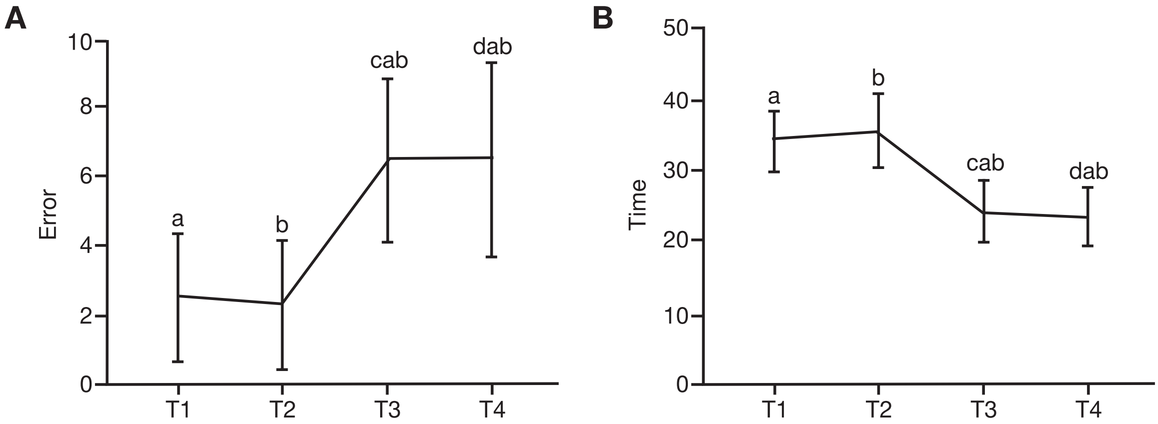

Figure 3. Comparison of error numbers (A) and time (B) between tasks in the electrical buzz wire test. The same letter indicates a statistically significant difference ($p < 0.05$)

From the data obtained in the linear regression to establish the relation between error and time during each task in the EBW test, equations were created for normalized values in this population:

Error = –0.31 + 0.08 × time (for task 1)
Error = 2.78 + 0.013 × time (for task 2)
Error = 9.11 – 0.11 × time (for task 3)
Error = 7.57 – 0.048 × time (for task 4)

The mean values of time obtained in each task were used to establish the number of normal errors in the EBW test in the population: 2.38 errors for 37 seconds in task 1; 3.2 errors for 35 seconds in task 2; 6.4 errors for 24 seconds in task 3; and 6.4 errors for 23.1 seconds in task 4.

The error and time variables in EBW presented weak correlations with all MABC-2 domains. The correlations are shown in Supplementary Table 1.

Discussion

EBW is an applicable tool to investigate object control skill in children aged 7–12 years. With the equations based on the mean execution times in the tasks, it was possible to relate the number of errors with the time of execution for this population. The findings indicate that our hypotheses were partially confirmed because a higher speed was related to a greater number of errors in EBW, independently of the level of difficulty determined by the size of the wire loop.

Some motor coordination tasks require the volunteer to perform with speed and accuracy. We often observe a speed-accuracy trade-off phenomenon. Fitts's law has played an important role in quantifying the speed-accuracy trade-off. According to Fitts [21], the time to do some activity is directly related to the speed used. With the inverse relation of velocity and accuracy of a movement, it leads us to conclude that with higher speeds, the accuracy is impaired [22]. Our methodological approach allowed us to visualize the differences between the tasks. In tasks 3 and 4, there was a change of strategy: *priority of speed over accuracy*, showing a higher number of errors and shorter execution time in EBW. In tasks 1 and 2, the chosen strategy was *priority of accuracy over speed*, implying a low number of errors and higher time of execution.

In the present study, we did not find a relationship between the wire loop sizes and number of errors in the tasks. However, we can assume that the type of control used was the cyclic or open-loop control in all tasks. This type of control results from pre-planned movement commands that are stored and then activated in the central nervous system (CNS). In 1960, Henry and Rogers [23] described the memory drum theory, which postulates that motor coordination patterns are stored in the form of neural patterns in the higher centres of the CNS, and predicts that simple reaction time increases with task complexity [23, 24]. In contrast, there are movements characterized as less cyclical or closed-loop controlled; these are thought to result from an initial movement command generated in the CNS that is subsequently adjusted or corrected as movement errors are detected [25–27]. Unfortunately, in our study, there was no task to activate this type of control, and maybe this is the cause of the same responses in the different wire loop sizes.

We highlight the importance of EBW association with manual dexterity of MABC-2, as there are specific coordination assessment tasks. We found a weak association ($r < 0.5$) between error/time in EBW and the MABC-2 manual dexterity and aim and catch items. According to French et al. [28], MABC-2, while useful in clinical settings and assessment of individuals, might not be as efficient for quantitative research and larger numbers of participants. Alves Bakke et al. [29] emphasized the divergence in the multidimensionality of MABC-2. This can compromise the practical utility of the test since the capacity to evaluate motor performance as predicted was not confirmed. The results of its subscales (manual dexterity, aiming and catching, and balance) should be interpreted with caution as they may be prone to errors.

We also did not use perceptual, visual, or cognitive scales, which can be considered a limitation of the present study. Despite these limitations, which can be solved in future studies, the tool used is easy to apply, constructed of low-cost material, and playful for the population. The instrument allows evaluation of movement control to guide a wire loop around a complicated wire track. During this task, controlled movements are necessary, such as hand grip, ulnar and radial deviations, wrist flexion and extension, pronation and supination of the forearm, and other shoulder and elbow movements. These movements are essential for the object control skill, including all necessary variables to guarantee a coordinated movement. We can infer the possibility of EBW use in other age ranges and also in specific disabilities.

Conclusions

EBW was developed and the results showed that the time and number of errors with a comfortable speed were lower when compared with high speed, regardless of the level of difficulty. Time and error values were also standardized in this age group (7–12 years). EBW is an interesting tool that could be more investigated and incorporated into the evaluation of eye-hand coordination and object control skill in children.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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Supplementary

Table 1. Associations between error and time variables in electrical buzz wire and Movement Assessment Battery for Children (total and domain scores)

Domains	Task 1		Task 2		Task 3		Task 4	
	Time (s)	Error (number of buzzing noises)	Time (s)	Error (number of buzzing noises)	Time (s)	Error (number of buzzing noises)	Time (s)	Error (number of buzzing noises)
Manual dexterity	$r = -0.05$ $p = 0.67$	$r = -0.06$ $p = 0.58$	$r = -0.12$ $p = 0.30$	$r = -0.27$ $p = 0.02$*	$r = -0.12$ $p = 0.34$	$r = -0.12$ $p = 0.34$	$r = -0.19$ $p = 0.12$	$r = -0.05$ $p = 0.64$
Aiming and catching	$r = -0.17$ $p = 0.17$	$r = -0.05$ $p = 0.69$	$r = -0.11$ $p = 0.38$	$r = -0.12$ $p = 0.35$	$r = -0.06$ $p = 0.63$	$r = -0.22$ $p = 0.07$	$r = -0.05$ $p = 0.68$	$r = -0.07$ $p = 0.58$
Balance	$r = -0.10$ $p = 0.42$	$r = -0.05$ $p = 0.68$	$r = -0.05$ $p = 0.67$	$r = -0.05$ $p = 0.65$	$r = -0.17$ $p = 0.17$	$r = -0.01$ $p = 0.93$	$r = -0.18$ $p = 0.13$	$r = -0.02$ $p = 0.90$
Total	$r = -0.17$ $p = 0.95$	$r = -0.05$ $p = 0.70$	$r = -0.11$ $p = 0.26$	$r = -0.30$ $p = 0.01$*	$r = -0.22$ $p = 0.04$*	$r = -0.19$ $p = 0.04$	$r = -0.35$ $p = 0.004$*	$r = -0.06$ $p = 0.91$

* statistically significant