

Fatigue-induced modifications to trunk and lower-limb coordination mode during drop vertical jump and sidestep cutting tasks in female handball athletes

Dayanne R. Pereira^{a,1}, Felipe A. Moura^{b,2}, Renato Moraes^{c,3}, Ana Luiza de C. Lopes^{d,4}, Luis Mochizuki^{e,5}, Paulo R.P. Santiago^{c,6}, Bruno L.S. Bedo^{a,*,7}

^a Laboratory of Technology and Sport Performance, School of Physical Education and Sport, University of São Paulo, São Paulo, Brazil

^b Laboratory of Applied Biomechanics, Sport Sciences Department, State University of Londrina, Londrina, Brazil

^c Biomechanics and Motor Control Laboratory, School of Physical Education and Sport of Ribeirão Preto, University of São Paulo, Ribeirão Preto, Brazil

^d Faculty of Physical Education, State University of Campinas, Campinas, São Paulo, Brazil

^e School of Arts, Sciences, and Humanities, University of São Paulo, University of São Paulo, São Paulo, Brazil

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ABSTRACT

Background: Examining movement patterns in athletic activities is crucial for understanding the mechanisms and contributing factors linked to lower limb injuries, with the knee joint being particularly vulnerable in team sports like handball.

Research question: How does a handball-specific fatigue protocol affect trunk-knee and hip-knee intersegmental coordination during the drop vertical jump (DVJ) and sidestep cutting maneuver (SCM) in handball players?

Methods: Twenty female handball athletes participated, performing three trials of each task before and after undergoing the fatigue protocol. Using a motion capture system, the trunk, hip, and knee joint angles were recorded in all three planes and time-normalized to 100% of the stance phase. A vector coding technique evaluated coordination nodes.

Results: This study indicated significant post-fatigue alterations in coordination modes, especially in the sagittal plane for DVJ and SCM tasks. There was an increase in knee phase modes and a decrease in in-phase modes for hip-knee coordination during the DVJ task, with transverse plane coordination being affected only in the SCM task. Movement variability decreased in the frontal and transverse planes post-fatigue, suggesting a neuromuscular strategy to simplify task execution.

Significance: Fatigue's significant impact on movement coordination and variability. It demonstrates the importance of considering the specificity of the task performed when setting up injury prevention training to mitigate the negative effects of fatigue and reduce the risk of injuries.

1. Introduction

Investigating movement patterns in athletic activities provides

essential information regarding mechanisms and contributing factors associated with lower limb injuries. The knee is one of the most injured joints in team sports athletes, and its prevalence is notable in handball

* Correspondence to: University of São Paulo, School of Physical Education and Sport, Av. Professor Mello Moraes, 65 - Vila Universitária, São Paulo, SP 05508-030, Brazil.

E-mail address: bruno.bedo@usp.br (B.L.S. Bedo).

¹ ORCID: 0000-0003-3752-8290

² ORCID: 0000-0002-0108-7246

³ ORCID: 0000-0001-8029-8334

⁴ ORCID: 0000-0002-4471-043X

⁵ ORCID: 0000-0002-7550-2537

⁶ ORCID: 0000-0002-9460-8847

⁷ ORCID: 0000-0003-3821-2327

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[1,2]. For instance, a non-contact anterior cruciate ligament (ACL) tear and anterior knee pain is a sports injury that commonly affects young female handball athletes [1,3]. These athletes engage in dynamic, high-impact movements, with abrupt shifts in the body's center of mass displacement combined with high positive and negative jerks, such as landings and direction changes [4,5], a common mechanism of injury associated with ACL rupture [6]. Furthermore, in handball, athletes must swiftly and accurately respond to external elements, leading to changes in joint mechanics and increased knee stress, especially during unanticipated sidestepping and landings [7,8].

The effect of fatigue on lower extremity kinematics and kinetics during dynamic tasks [9–11] suggests significant changes in how the body moves due to fatigue [12]. Such impairments as decreased movement efficiency can potentially increase the risk of injury as they impair the proper stabilization and coordination during intense activities [13]. Studies traditionally do not associate lower limb joints' kinematics and kinetics [14], excluding the interaction and influence between the proximal and distal joints used during a task. It is crucial to address the modifiable risk factors for knee injuries, such as the lower limb kinematics—like hip flexion and internal rotation, knee flexion, and knee valgus [7,9,15,16] and which can be modified, presenting a greater or lesser range of joint movement, due to trunk movement [8, 17].

Once these risk factors and their relationships are understood, they can be controlled or prevented with training programs to reduce or prevent injuries in sports [18]. The relationship between the coordination of the trunk and lower limbs can be observed by the increased risk of ACL injury when the athlete presents an altered trunk movement, as the increase of trunk inclination [19]; therefore, the isolated analysis of the segments is not enough to understand the control and mechanics of the joints of the lower limbs in terms of the appearance of injuries, since the distal segments, such as the trunk, appear to have a great influence on the control and positioning of the lower limbs [20].

Movement variability in athletic performance and the etiology of musculoskeletal injury onset have been extensively studied. It has been used to represent the plasticity of the motor control system in adapting, through intersegmental restructuring and organization, to changes imposed by the external and internal environment, such as in fatigue [21], and it provides the metrics to understand which coordinative modes are maintained in different situations and what consequences these patterns can have on the musculoskeletal system [22]. Variability in movement coordination has already been related to lower limb injuries. The system's self-reorganisation characteristic to perform the same effort during a task has been debated [23,24]. While some studies have shown an increased joint variability in fatigue [25], others suggest that variability decreases under these conditions [26].

Considering the kinematic patterns of athletic tasks, different techniques have been used to investigate body segment coordination, such as relative motion plots [26,27] and continuous relative phases (CRP) [28], to describe the movement technique and performance [29]. However, these techniques have limitations in handling non-sinusoidal movements and trials of variable lengths [30]. Vector coding, nevertheless, stands out for its simplicity and efficiency, especially in comparing multiple trials of different lengths and non-sinusoidal motion patterns [26,31]. The subsequent quantification of coordination variability shows that vector coding provides a more in-depth sensitive measure to suppress changes in joint coordination variability compared to the traditional kinematic analysis [27].

Since decreased coordination variability might lead or not to the adaptability of coordination to external changes during athletic activities, potentially increasing the risk of injuries [32], this study aimed to explore the effects of a handball-specific fatigue protocol on trunk-knee, trunk-hip, and hip-knee coordination modes, during the drop vertical jump (DVJ) and sidestep cutting maneuver (SCM) tasks. We hypothesize that fatigue will negatively influence the adaptability of the joint system during the task; that is, we believe that under fatigue, there will be no

changes in the pattern of intersegmental coordination, reducing the variability of motor responses that the body can present to respond in different ways to the same task. We also hypothesize that fatigue will induce increased “freezing” motion in proximal joints/segments, leading to a greater need for coordination adaptation in distal joints, and increasing the risk of lower limb injuries.

2. Methods

2.1. Participants

Twenty female collegiate handball athletes (mean age: 21.9 ± 3.4 years; weight: 63.5 ± 9.1 kg; height: 1.76 ± 0.07 m; experience: 7.2 ± 3.2 years) comprised the sample. This sample size achieved a statistical power of 0.97 ($\alpha = 0.05$; effect size = 0.83) to detect differences between baseline and fatigue-state values. Power analysis was conducted using G*Power software (version 3.1.9.2, Dusseldorf, Germany), with maximum propulsion force selected as the primary outcome variable [33]. The local Ethics Committee approved the study protocol, and each athlete provided written consent to participate.

2.2. Fatigue protocol

The fatigue protocol, designed to replicate movements commonly performed in handball practice, was conducted in a lab setting and structured as a circuit (see [34] for further details). Each participant performed the protocol individually during their usual practice hours to align with typical training conditions. Participants were instructed not to engage in strenuous physical activity the day before testing to ensure baseline recovery. The protocol began with two initial circuits for familiarization and warm-up, followed by rounds with progressively increasing volume based on the number of laps, with each round performed as quickly as possible. Athletes' fatigue levels were monitored using the rate of perceived exertion (RPE) scale [35], with testing concluding once the athlete reached a self-reported exhaustion level that prevented further participation. Additionally, participants were only included in additional testing if they could complete the protocol. Athletes could stop the protocol if they felt discomfort or exhaustion.

2.3. Experimental procedure

Athletes completed three trials for each task in sequence: the drop vertical jump (DVJ) and sidestep cutting maneuver (SCM). In the DVJ, participants began by stepping off a 40-cm-height box. Upon touching the ground, they were instructed to land with both feet simultaneously and immediately jump as high as possible. A successful trial was characterized by a synchronized foot landing and maintaining a steady posture following the jump. For the SCM, athletes sprinted for four meters, performed a 45° sidestep cutting on their non-dominant leg, and continued to run for an additional three meters. Success was determined by the athletes' ability to remain within the boundaries of the coloured tape placed on the ground, which indicated the direction of the sidestep maneuver.

2.4. Instrumentation and data analysis

A motion capture system with eight cameras (MX-T40S, Vicon, Oxford, UK) recorded the movements of reflective markers at 250 Hz. These passive reflective markers were placed on participants' skin at defined landmarks by the University of Ottawa Motion Analysis Model (UOBAM) marker set [36]. The data were reconstructed, labelled, and subsequently filtered with a zero-lag, 4th-order Butterworth filter set at 6 Hz using the Nexus 2.8 software (Vicon Motion Systems Ltd., Oxford, UK). The trunk, hip, and knee joint angles were determined using anatomical coordinates within the local system, with a rotation sequence of X-Y'-Z". Each segment had its coordinate system. From the

system’s definition, we have calculated the Euler angles [37], considering the cervical as a fixed segment and the pelvis as a mobile segment. Calculating the hip (pelvis as fixed and thigh as mobile segment) and knee (thigh as fixed and leg as mobile segment) angles will be the same. These angles were compared to the neutral position established during an upright stance. All joint angles were time normalized, spanning 0–100 % of the stance phase.

Fig. 1 shows the vector coding analysis process. It begins with the time-normalized series of the target joint angles (Fig. 1A and B). The subsequent step captures the relative movement between the two focal joints, demonstrated in the figure by the knee and hip in both baseline (Fig. 1C) and fatigue conditions (Fig. 1D). These movements are visualized in angle-angle diagrams, showcasing changes in joint angular rotations. A coupling angle (γ) is derived from the diagrams, representing the relative movement between the two segments. Coordination modes are then evaluated based on this coupling angle, which is determined by the angle between a vector connecting two consecutive time points and the horizontal axis on the right. The relationship between consecutive γ values is assessed using the vector coding technique [26,31,38], resulting in a time series of coupling angles (Fig. 1D). Subsequently, histograms are generated to classify the identified coordination modes (Fig. 1E).

The coupling angle captures the immediate spatial relationship, from which four specific coordination modes can be discerned: i) anti-phase, ii) in-phase, iii) primary joint phase (trunk or hip), and iv) second joint phase (hip or knee). A joint phase means the dominant movement of one joint relative to another. For example, the hip predominantly moves during the hip phase while the knee remains largely stationary, moves minimally, or presents a time-lag motion in relation to the hip.

Coupling angles align with one of the coordination modes (Table 1). Using bins of 45° for classification [26], a γ of 45° or 225° denotes an in-phase coordination mode when both joints rotate synchronously (for instance, both the hip and knee flex in tandem). Conversely, $\gamma = 135^\circ$ or 315° means an anti-phase coordination mode, indicating that the joints rotate in opposing directions. The coupling angles 0°, 90°, 180°, and 270° highlight the predominant coordination mode of a single joint. For each condition (baseline and fatigue), we computed the frequency representation of each coordination mode (in-phase, anti-phase, primary

Table 1
Ranges of the coupling angles used to classify the inter-segmental coordination modes (in-phase, anti-phase, trunk, hip, and knee modes).

	Coordination modes	Coupling Angle Ranges
Trunk vs Hip	Anti-Phase	$112.5^\circ \leq \gamma < 157.7^\circ, 292.5^\circ \leq \gamma < 337.5^\circ$
	In-Phase	$22.5^\circ \leq \gamma < 67.5^\circ, 202.5^\circ \leq \gamma < 247.5^\circ$
Trunk vs Knee	Trunk Phase	$0^\circ \leq \gamma < 22.5^\circ, 157.5^\circ \leq \gamma < 202.5^\circ, 337.5^\circ \leq \gamma < 360^\circ$
	Hip Phase	$67.5^\circ \leq \gamma < 112.5^\circ, 247.5^\circ \leq \gamma < 292.5^\circ$
Hip vs Knee	Trunk Phase	$0^\circ \leq \gamma < 22.5^\circ, 157.5^\circ \leq \gamma < 202.5^\circ, 337.5^\circ \leq \gamma < 360^\circ$
	Knee Phase	$67.5^\circ \leq \gamma < 112.5^\circ, 247.5^\circ \leq \gamma < 292.5^\circ$
Hip vs Knee	Hip Phase	$0^\circ \leq \gamma < 22.5^\circ, 157.5^\circ \leq \gamma < 202.5^\circ, 337.5^\circ \leq \gamma < 360^\circ$
	Knee Phase	$67.5^\circ \leq \gamma < 112.5^\circ, 247.5^\circ \leq \gamma < 292.5^\circ$

joint, and the specific joint based on the analyzed coordination pair) in flexion/extension, adduction/abduction, and internal/external rotation. The joint coupling variability was assessed for each participant by computing the circular standard deviation at each time node over the four trials. Subsequently, each node’s average and standard deviation were determined across the group, providing a non-angular variability metric between trials for every condition.

2.5. Statistical analysis

We employed specific statistical methods to assess variations in coordination modes determined through the vector coding technique (including anti-phase, in-phase, trunk or hip phase, and knee phase) before and after the fatigue protocol for SCM and DVJ tasks. First, each data set underwent the Shapiro-Wilk test to check for normality. The frequency of each coordination mode is presented as its median, accompanied by a confidence interval. The frequency of each coordination mode did not follow a normal distribution, so we applied the arcsine transformation. Subsequently, we used the repeated measure ANOVA with two factors: experimental condition and phase mode. If sphericity assumptions were unmet, we applied the Greenhouse-Geisser correction. Upon detecting significant F-ratios, we conducted Bonferroni

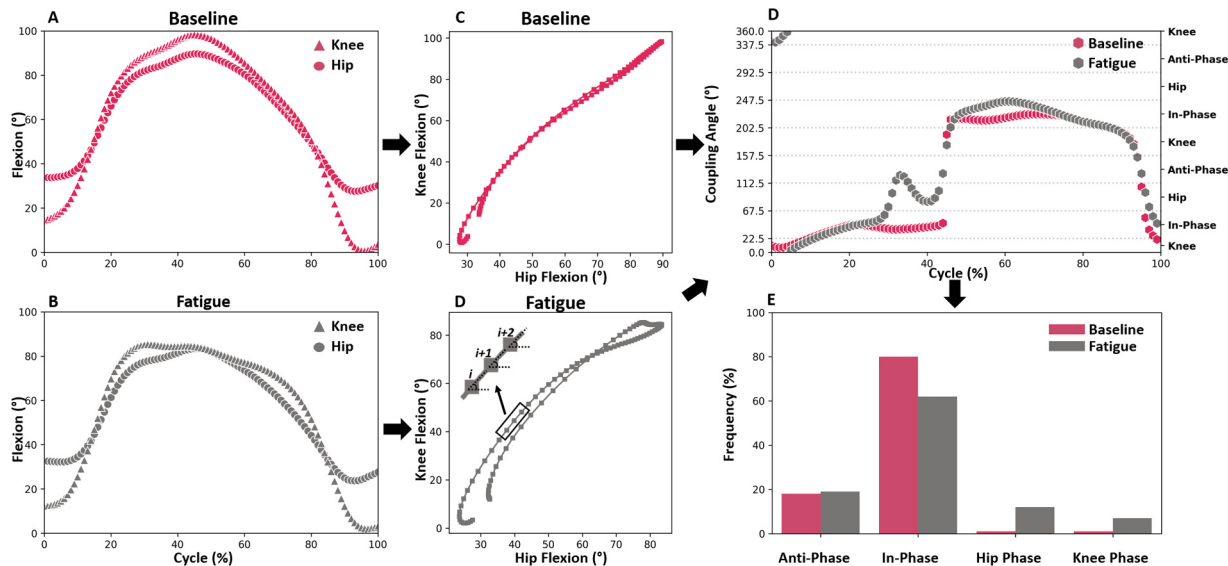


Fig. 1. This schematic provides an overview of the methodology adopted within the vector coding technique to discern coordination modes. On the left, the diagram illustrates the temporal progression of angular data for both the hip and knee joints, represented by a triangle and a ball, during an athlete’s execution of the drop vertical jump under baseline (A) and fatigue (B) conditions. The central plots offer insight into the angle-angle relationship of the hip-knee angular data captured during a single trial, both in baseline (C) and fatigue (D) scenarios, with a particular emphasis on the computation of the coupling angle (γ). The top-right graph (E) traces the temporal evolution of these coupling angles. The bottom-right section features histograms that categorize the detected coordination modes (F). Red and gray correspond to the baseline and fatigue conditions, respectively.

post-hoc comparisons to identify specific points of difference. The median and interquartile ranges of the coordination variability are presented. Since it followed a normal distribution, a paired T-test was employed to compare the coordination variability between pre and post-fatigue protocol. Cohen's d standardized effect sizes are reported when appropriated. A significance level of $p < 0.05$ was set up throughout this analysis.

3. Results

3.1. Drop vertical jump

The effects of fatigue on the coordination among the trunk-hip, trunk-knee, and hip-knee segments are illustrated in Fig. 2. The coordination during the DVJ was affected solely in the sagittal plane for both trunk-knee ($F = 4.31$, $p = 0.008$) and hip-knee pairs ($F = 3.49$, $p = 0.04$). Concerning the trunk-knee pair, the knee phase increased after a fatigue protocol ($p < 0.001$, $d = 1.28$). For the hip-knee pair, the in-phase mode decreased after a fatigue protocol ($p = 0.04$, $d = 0.55$). Regarding the frontal and transversal planes, no effect of fatigue was observed in any of the three pairs (trunk-hip, trunk-knee, and hip-knee). The joint coupling variability is presented in Fig. 3. Significant increases after fatigue protocol were found in the transversal plane for the trunk-knee ($p = 0.043$, $d = 0.58$) and hip-knee ($p = 0.003$, $d = 0.66$) pairs.

3.2. Sidestep cutting maneuver

For the intersegmental coordination modes during the SCM task, only the transverse plane was affected by fatigue (Fig. 4). The trunk-hip pair ($F = 3.20$, $p = 0.03$) exhibited a decrease in the in-phase mode under fatigue ($p = 0.021$, $d = 0.78$). For the hip-knee pair ($F = 3.09$, $p = 0.03$), we observed both a decrease in the in-phase mode ($p = 0.008$, $d = 0.84$) and an increase in the anti-phase mode ($p = 0.028$, $d = 0.66$). In contrast to the DVJ task, a significant decrease in joint coupling variability was found after the fatigue protocol. This was observed in the frontal plane for the trunk-knee ($p = 0.033$, $d = 0.41$) and hip-knee ($p = 0.003$, $d = 0.88$) pairs, as well as in the transverse plane for the trunk-hip ($p = 0.005$, $d = 0.37$) and trunk-knee ($p = 0.026$, $d = 0.41$) pairs.

4. Discussion

This investigation focused on verifying the effect of fatigue caused by the handball-specific protocol on the trunk-hip, trunk-knee, and hip-knee pairs and variability during DVJ and SCM tasks. We hypothesized that fatigue would negatively influence the adaptability of the joint system and induce increased “freezing” motion in proximal joints/segments during the tasks. Our results showed that fatigue altered coordination modes in the sagittal plane for both trunk-knee and hip-knee pairs for the DVJ, while no effect of fatigue was observed for all three

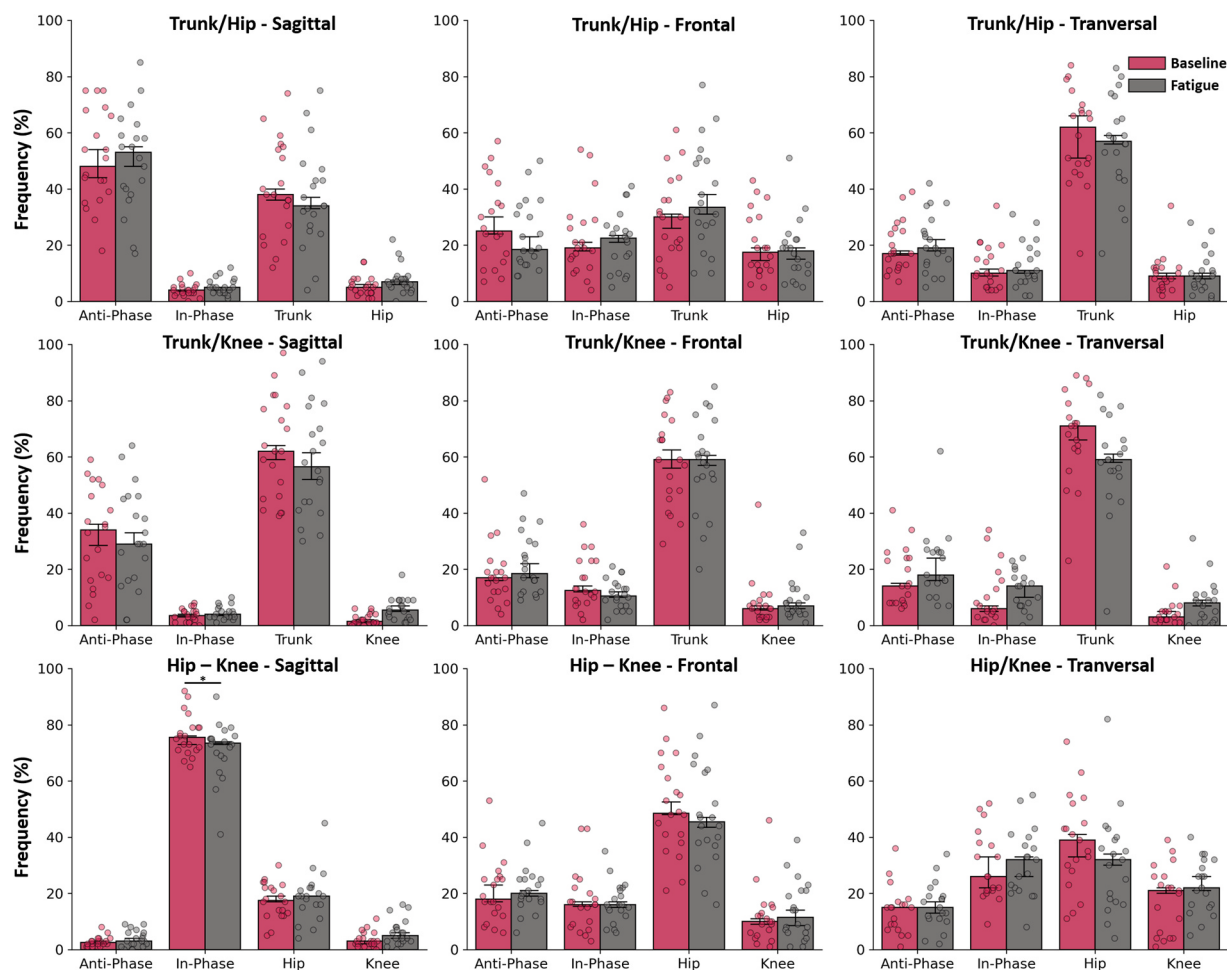


Fig. 2. Histograms displaying coordination modes under baseline (red) and fatigue (gray) conditions (group medians $\pm$ confidence interval) during the drop vertical jump task. The upper graphs depict trunk-hip coordination, the middle graphs represent trunk-knee coordination, and the lower ones illustrate hip-knee coordination. From left to right, the graphs represent the sagittal, frontal, and transversal planes, respectively. Coordination was analyzed across four modes: Anti-Phase, In-Phase, Trunk or Hip Phase, and Knee or Hip Phase. Symbols (*) within the histograms denote significant differences between Baseline and Fatigue Conditions ($p < 0.05$).

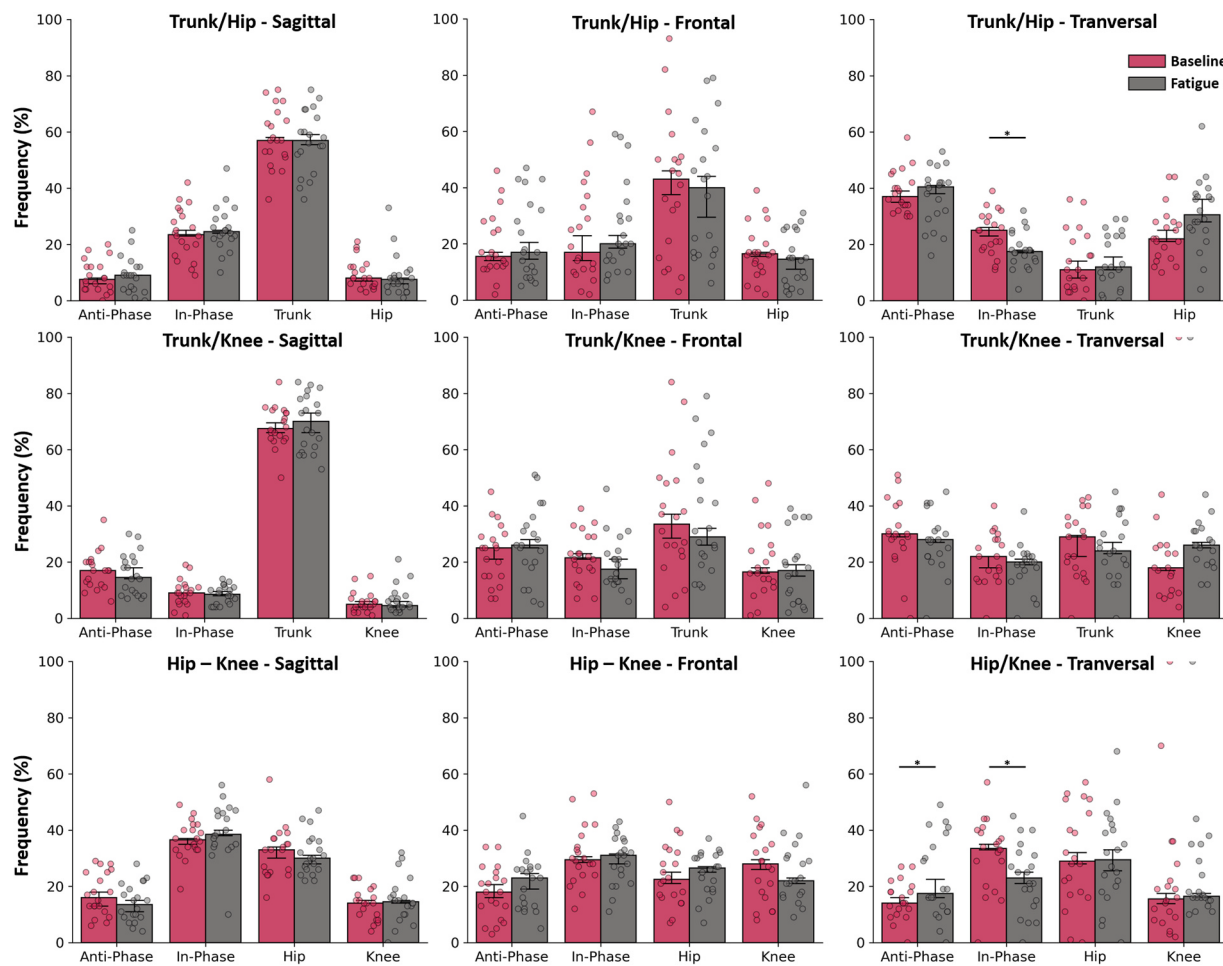


Fig. 3. Histograms displaying coordination modes under baseline (red) and fatigue (gray) conditions (group medians $\pm$ confidence interval) during the sidestep-cutting task. The upper graphs depict trunk-hip coordination, the middle graphs represent trunk-knee coordination, and the lower ones illustrate hip-knee coordination. From left to right, the graphs represent the sagittal, frontal, and transversal planes, respectively. Coordination was analyzed across four modes: Anti-Phase, In-Phase, Trunk or Hip Phase, and Knee or Hip Phase. Symbols (*) within the histograms denote significant differences between Baseline and Fatigue Conditions ($p < 0.05$).

pairs in the frontal and transverse planes. For the SCM task, the fatigue protocol only affected coordination in the transverse plane. Concerning the coordination variability, there was a significant decrease for the SCM task after fatigue, in contrast to the increase in coordination variability for the DVJ task.

Changes in coordination depend on the nature of the task. The effects of fatigue on the coordination were only observed in the sagittal plane for the drop vertical jump, which is a typically sagittal plane task, while it was found in the transverse plane for the sidestep cutting maneuver. Maintaining constant the objective of the task, human movement variability reflects on the kinematics and kinetics variability displayed between repetitions [39]. Thus, one of the most important features of the neuromuscular system is its ability to adapt. During fatigue, the neuromuscular system can use compensatory strategies to mitigate the impact of fatigue, maintaining the performance of motor actions [40]. Our results confirmed this at the joint level, supporting the notion that fatigue requires adjustments in intersegmental coordination to meet the requirements of a task. Such modifications in motor behaviour, often called “compensatory strategies”, aim to maintain uniform power production [41]. Contrary to what we suggested, our study showed changes in the spatiotemporal characteristics of the movements, emphasizing that the neuromuscular system responds to fatigue by adopting different patterns of motor coordination; however, some of these modes can pose risks to the joint, as they can alter the joint mechanics due to fatigue, which can increase the risk of injury [28].

The effects of fatigue on coordination variability are task-dependent. Our results showed a change in coordination variability in both tasks, even though they were in opposite directions, increasing variability during the DVJ and decreasing it during the SCM. Three different explanations are possible for the lower coordination variability. Hamill et al. [22] explained the variability under the concept of “endpoint”, when the movement variability will be lower in more experienced and healthy people and greater in inexperienced or unhealthy individuals (e.g. with patellofemoral pain) [39]. An alternative to the “endpoint” view is that what is important for stability in the task performance is the coordination variability in the task, and that these two concepts of variability must be integrated into any functional analysis of movement. That is, coordination variability at the endpoint of the task should not be analyzed apart from the variability of adjacent structures [22].

Lipsitz [42] presented the “loss of complexity” hypothesis. They suggest the lack of variability may be a characteristic of performance dysfunction, frailty, or illness, and it could be a system strategy to make movements more rigid or make the task simpler, aiming to achieve better joint stability to perform the task without decreasing or impairing its performance [39,43]. However, reductions in the degrees of freedom, components’ interaction, and the synergies involved in controlling the biological system may be associated with a loss of variability. In this way, different combinations of intersegmental coordination can be performed, giving the joint system the potential to achieve different modes of coordinative variability. Nonetheless, when these reductions

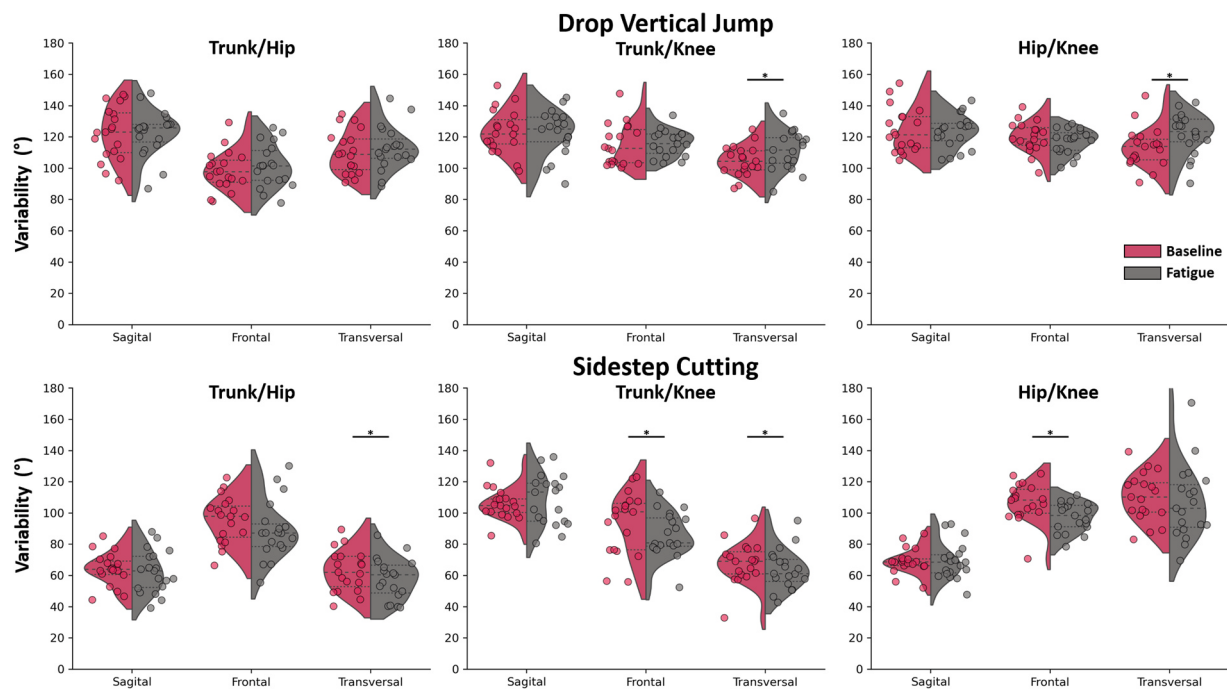


Fig. 4. Violin plots display coordination variability under baseline (red) and fatigue (gray) conditions. The plots show the medians (central mark) and quartiles (dashed lines) to underscore the distribution's spread and central tendency. The upper graphs depict the drop vertical jump task, while the upper graphs depict the sidestep cutting maneuver task. From left to right, the graphs represent the trunk-hip, trunk-knee, and hip-knee, respectively. Variability was analyzed across the sagittal, frontal, and transversal planes. Symbols (*) within the histograms denote significant differences between Baseline and Fatigue Conditions ($p < 0.05$).

in degrees of freedom and variability reach a critical threshold, the number of combinations is reduced, suggesting the appearance of injuries or other diseases.

On the other hand, increased variability in fatigue situations may indicate the recruitment of different structures, such as joints and muscles, to assist in movement, offering the joint system greater flexibility to adapt motor responses in varying contexts [24,25]. The observed decrease in in-phase coordination between the hip and knee, along with the increased knee phase in the trunk-knee pair during the DVJ task, suggests that fatigue may impair the ability of multiple joints to move simultaneously in the same direction. Given that the DVJ is a load absorption task, the knee muscles are particularly engaged during the absorption of impact forces, which could explain the reduced trunk movement relative to the hip and knee. As hypothesized, our results show a tendency towards "freezing" of the proximal joints, with a greater reliance on the distal joints, placing additional tension on the knee ligaments during the task.

Luy et al. [44] and Fang et al. [45] found that, in a fatigued state, anticipatory control (also called feedforward strategies) takes longer to initiate. This means the neuromuscular system delays its response to a task when fatigued. Specifically, after the fatigue of the lower limb muscles, the muscles of the core and abdominal regions may experience a delayed onset of co-contraction when recruited to assist in completing the task. This delayed activation may help explain why "freezing" is more noticeable in the trunk or joints proximal to the trunk.

Greater knee movement in relation to the hip and trunk may also represent a greater contribution of the legs for propulsion right after landing. Once we identified a pattern of less "contribution" to the movement by the proximal segments, the entire force production and propulsion chain would be dependent on the knee joint and leg muscles such as the calf, which would also cause an increased knee joint overload, as the hip extensors would not be, in a situation of fatigue, moving from their maximum stretching to their maximum contraction, reducing their action on the task. Therefore, maintaining adequate knee flexion to prevent injuries occurs during the weight acceptance phase, after the initial contact with the ground [46], especially when the knee is almost

fully extended [2]. Insufficient knee flexion impairs the joint's shock absorption, stressing its internal structures, so the limited knee flexion can change lower limb biomechanics, raising injury risk [47,48].

During the DVJ task, fatigue affected the frequency of coordination modes in the trunk and hip-knee phases only at the sagittal plane. As muscles are fatigued, their capacity to produce force and regulate movement wanes. The primary stabilizing muscles may fatigue faster than others, prompting a dependence on auxiliary muscles. For instance, a previous study on the increased internal rotation of the knee right after heel contact during impact absorption suggests challenges in controlling knee movement in the transverse plane when the hamstrings are fatigued [49]. Similarly, when only the hamstrings were fatigued, there was a decrease in hip-knee rotation, implying that muscular fatigue adversely affected dynamic knee joint stability [13]. Secondly, athletes might adopt compensatory movement strategies to maintain fatigued performance levels. This can involve using different muscle groups or changing joint kinematics, as we mentioned above, which can inadvertently lead to increased knee rotation.

The manifestations of fatigue-induced kinematic changes largely hinge on neuromuscular control, with origins rooted in neural factors. As fatigue sets in, metabolic by-products accumulate in the muscles, disrupting muscle fiber functionality and altering force output [50]. Furthermore, fatigue can impair sensory feedback mechanisms vital for proprioception, impacting the body's spatial recognition. The cognitive repercussions of fatigue—marked by diminished attention and decelerated reaction speeds—can alter movement execution and timing [50]. The findings of altered coordination modes in the sagittal plane during the DVJ may relate to the notable effects of fatigue on dynamical coordination as a cognitive process in various exercises [51].

Moreover, the implications of fatigue-induced kinematic changes on joint stability and injury risk have been discussed by [52], who found that metabolic fatigue impairs dynamic knee joint stability in young women athletes during dynamic tasks, potentially increasing the risk of knee injuries. Additionally, Hiemstra et al. [53] showed how fatigue can alter neuromuscular control of the lower limb, affecting an individual's ability to stabilize the knee joint dynamically through altered

proprioception. The lower limb encompasses several joints, which operate in an interconnected manner, where the movement of one can influence another. However, our results suggest that the nature of the movement can impact the trunk-hip and hip-knee coordination.

Furthermore, our results also indicate greater trunk movement in relation to the hip and knee under baseline conditions. Although it is not statistically relevant, when we talk about the scope of clinical and sports practice, a scenario in which the body is under fatigue conditions, this movement of the trunk reduces, again inferring the freezing tendency of the proximal segments under fatigue conditions, reducing the contribution of the trunk and allowing movement of the hip and knee joint. Another important aspect of our results is the alert to an increase in the rotational mechanism in opposite directions between the hip and knee during SCM. We believe that during SCM, knee flexion increased relative to pre-fatigue values due to increased and opposite rotation of both hip and knee.

Biomechanically, the knee only allows rotational movements when flexed, as the joint is “unlocked”, which enables a range of movement, albeit small, in the transverse plane. The most common mechanism of injury to the ACL described in the literature occurs precisely when the knee is in semi-flexion, with rotation of the tibia (external) and femur (internal) in opposite directions, which was presented in our results (increase of the hip-knee anti-phase), along with ipsilateral trunk inclination in fatigue situations. Although we cannot say in which direction the rotation of each segment (thigh and shank) is occurring, the movement of rotation in opposite directions represents a risk for increased injuries to the lower limb, especially concerning the knee joint [54].

The SCM and DVJ tasks demonstrate different kinematics and neuromuscular demands, with the SCM task emphasizing lateral movements and rapid directional changes, introducing distinct coordination modes and potential joint stressors. These activities highlight the complexity of muscle force generation, joint stability, and motor control strategies, especially under fatigue. For instance, fatigue-induced changes in trunk-hip and hip-knee coordination during the DVJ task, which requires precise control for landing, indicate a compensatory shift in movement patterns to redistribute loads across joints and muscles, reducing stress on fatigued muscles. In this way, there is a window of coordination variability that is considered healthy as long as the movement is in a balance of variations in coordinating modes, presenting neither too much increase in variability nor a very significant reduction; that is, there is an ideal or healthy state in the joint system, capable of responding to the same tasks with different solutions [22].

However, we cannot exclude the possibility that this load redistribution may lead to abnormal joint loading and an increased injury risk [39]. The variations in biomechanical responses to fatigue between the DVJ and SID tasks underscore the specificity of neuromuscular adaptations to different athletic movements, stressing the importance of considering each sports activity's distinct biomechanical and neuromuscular demands in injury risk assessment and training program design. This specificity suggests that generalized training or rehabilitation may not suffice, potentially leaving athletes more prone to injury during specific movements. Therefore, a more tailored approach to training and rehabilitation, addressing the particular demands of different sports activities, could be more effective in minimizing injury risks and enhancing athletic performance.

From a practical perspective, our findings help professionals to incorporate targeted exercises that address fatigue-induced coordination changes, particularly focusing on trunk and lower limb stability during dynamic tasks like jumping and sidestep cutting. Implementing task-specific drills under controlled fatigue conditions could help athletes build resilience against coordination losses, potentially reducing injury risks during late-game situations when fatigue is highest.

Despite the challenges in prescribing and ensuring effective prevention of sports injuries—given the multifaceted determinants and complexity of their occurrence [55,56]—integrating knowledge about

the duration of fatigue effects on the neuromuscular system [57] with strategies to enhance the body's capacity to manage and mitigate fatigue could provide valuable insights for developing task-specific preventive training programs. These programs may offer effective and targeted approaches to reducing injury incidence and severity.

This investigation has limitations, as the research was conducted in a controlled laboratory environment. While we employ a fatigue protocol and motor tasks that mimic those executed during handball training to achieve ecological validity, future research must be carried out on an actual handball court using a real game to induce fatigue. Furthermore, although we utilized a sport-specific method to cause fatigue, it does not equate to genuine game scenarios, which we recommend exploring in future studies.

5. Conclusion

Fatigue significantly affected trunk and lower limb coordination during DVJ and SCM tasks, suggesting that athletes may adapt their movement patterns as compensatory strategies to maintain performance. These adjustments likely counterbalance the harmful effect of fatigue in movement coordination. This study shows the importance of further research into joint-specific responses to fatigue and movement coordination variability, mainly focusing on landing techniques, in light of the mechanism of knee injuries. A deeper understanding of fatigue-related task-specific coordination changes could enhance future injury prevention programs by addressing fatigue-induced neuromuscular adaptations.

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CRediT authorship contribution statement

Renato Moraes: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Ana Luiza C. Lopes:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Data curation. **Dayanne R. Pereira:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Felipe A. Moura:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Investigation, Funding acquisition, Formal analysis, Data curation. **Paulo R. P. Santiago:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Bruno L. S. Bedo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Luis Mochizuki:** Writing – review & editing, Supervision, Methodology, Formal analysis.

Declaration of Competing Interest

The authors have no conflicts of interest to declare.

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