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Beyond Simple Tapping: Is Timed Body Movement Influenced When Balance Is Threatened?

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Abstract: The tapping paradigm offers valuable insights into movement timing; however, it simplifies mechanics by minimizing force, restricting motion, and relying on a clear contact endpoint. Thus, it may not fully capture the complexity of larger-scale multi-segmental (or single-segment) timed body movements. The aim of this study was to extend beyond the tapping paradigm by examining the timing of two large-scale movements commonly performed in physical fitness or rehabilitation modalities, with varying inherent balance threats: two-legged squatting (low balance threat) and standing hip abduction (higher balance threat) paced by a metronome set at the participants' preferred tempo (N = 39, all physically active). In synchronization with the metronome audio signal, the trunk and shank angular velocities were also recorded to extract the entrainment, synchronization, and pace stability metrics. Paired *t*-tests indicated similar entrainment in both movements ($p > 0.05$ for IRI match) but significant differences in timing metrics' manifestations ($p \leq 0.05$, standing hip abduction: 50% greater IRI error, 30% lower synchronization error, 2.6% units lower pace stability). The similar entrainment but different synchronization error and pace stability highlight a complex timing interplay between balance threat/challenges and movement complexity concerning the two large-scale movements employed in physical fitness and rehabilitation modalities.

Keywords: entrainment; synchronization; pace stability

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1. Introduction

The ability to temporally align/synchronize body movements with external auditory stimuli (metronome or musical beats) plays a fundamental role in human motor performance across a range of activities, from everyday functional work activities and social tasks (e.g., dance) to recreational or competitive sports [1–4]. This phenomenon, known as timed movement [5], encompasses three fundamental timing aspects, all of which contribute to effective temporal alignment of bodily actions to external rhythmic cues (e.g., auditory cues): entrainment, synchronization, and pace stability [5,6].

Entrainment refers to the general capability of matching movement frequency with an external cue, such as a metronome or music, without necessitating the exact concurrence of a discrete motor event to a discrete sound event [4,6,7]. It reflects the broader ability to match the pacing period or movement frequency over time, typically assessed through metrics like the relationship between the inter-response interval (IRI) and the inter-stimulus interval (ISI) [4,6,8,9]. The accuracy of entrainment is often quantified using the IRI synchronization error, which measures the difference between IRI and ISI, thereby highlighting the concept of period correction, where adjustments are made to match IRI with ISI [6,8], with higher IRI error values indicating lower entrainment accuracy.

Synchronization differs from entrainment by requiring the accurate alignment of self-initiated movements with specific points in the external pacing source. This process involves sophisticated sensorimotor adjustments and error correction mechanisms [8]. Synchronization accuracy is measured by the synchronization error metric, which quantifies the temporal discrepancy between the stimulus pacing event (e.g., auditory beat onset) and the movement event (e.g., movement onset) [4,6,8,10]. Synchronization error introduces the concept of phase correction, where adjustments are made to align specific movement points with specific pacing events [8].

Pace stability evaluates the consistency of movement timing without explicit reference to a cue, and it is quantified by assessing the within-subject variability in IRI using the coefficient of variation of IRI (IRI CoV) [11,12]. This metric underscores the ability to maintain rhythmicity despite inherent variability in motor execution. While not directly related to aligning with external cues (as in entrainment and synchronization), pace stability provides valuable insights into the underlying mechanisms allowing for the maintenance of consistent movement timing. Biénkiewicz and coworkers [11] highlight the temporal goal of the task as more crucial for pace stability and movement organization than movement scale, timing strategy, and accuracy demands. Similarly, Rodger and Craig [2] found that longer interval durations are associated with greater variability in timing performance.

The classical studies of timed movement use the established finger-tapping paradigm [2,4,8,11,13]. Although this approach has provided valuable insights into timing control, it simplifies movement mechanics by minimizing force, limiting motion, and offering clear spatial endpoints [2,4,11,13,14]. Consequently, finger tapping cannot fully capture the complexity of larger-scale movements, where distinct strategies naturally emerge, such as when moving a finger between targets aligned with auditory cues [2,11] or performing more complex movements such as timed multi-segmental (or single-segment) body movements, as often occurs in physical fitness and rehabilitative modalities. Evidence suggests that movement complexity may influence the process of temporal correction under a synchronization constraint, with simpler movements showing larger corrections (e.g., finger tapping in place) than more complex ones (e.g., stepping in place) [15]. However, there appears to be a lack of data concerning the timing aspects of complex and large-scale multi-segmental (e.g., squatting) or single-segment (e.g., lower or upper extremity abduction/adduction, flexion/extension) body movements as those typically employed in physical fitness or rehabilitative modalities.

These more complex large-scale or single-segment movements differ from finger tapping in several key ways. They require greater muscular force and involve a wider range of motion. However, the most important difference most likely lies in the sensory information providing the movement's endpoints, which is considered to play a significant role in movement timing and temporal accuracy [2]. In finger tapping, surface contact provides clear spatial cues that help determine the precise moment of action. In contrast, the multi-segmental or single-segment movements used in fitness and rehabilitation rely more on proprioceptive cues, as there are no explicit contact points. As a result, these movements depend less on explicit temporal representation and more on implicit timing, where regularities are derived from movement variables rather than direct time cues [13].

A key factor that may influence the timing of these large-scale movements is the threat to balance. For example, exercises like standing hip abduction, performed on one leg, present a greater balance challenge compared to two-legged squatting, which benefits from a wider base of support. Understanding how the balance threat affects timing is essential, especially for movements constrained to align with auditory cues. Previous research highlights a connection between balance and timing [16]. In particular, Chen and coworkers [16] found that higher balance demands, such as standing, resulted in slower compensation for metronome timing shifts (increased synchronization error), though the overall variability remained unaffected. Similarly, Gabbard and Hart [17] also observed fewer taps during single-leg standing compared to seated tapping, further suggesting that balance threats can impact timing performance.

Considering the limitations of the tapping paradigm (finger or foot tapping), research should extend to more complex and large-scale multi-segmental or single-segment timed movements, without explicit external spatial sensory feedback. Such an approach would provide a more ecologically valid context for studying sensorimotor synchronization at movement conditions where the participants themselves set the spatial boundaries, such as the depth of a squat or the range of motion in standing hip abduction.

The aim of this study was to investigate the timing of movement beyond the tapping paradigm, employing two large-scale movements commonly performed in physical fitness or rehabilitation modalities, performed without contact surface endpoints, as occurs in the tapping paradigm and with varying inherent balance threats: the two-legged squatting (low balance threat) and the standing hip abduction (higher balance threat).

We hypothesized that movement timing would differ between the two-legged squatting and the standing hip abduction due to the inherent balance threat in the latter. In particular, we expected similar entrainment measures but different temporal accuracy reflected at reduced pace stability and increased timing errors (entrainment error and synchronization one).

2. Materials and Methods

2.1. Participants

In this study, 39 active men (n = 20) and women (n = 19) participated (age: 25.2 ± 4.6 and 24.4 ± 4.4 years, body height: 1.80 ± 0.07 m and 1.65 ± 0.05 m, body mass: 81.4 ± 11.3 kg and 70.7 ± 14.6 kg, for men and women), respectively, with various sports backgrounds, such as basketball, football, gymnastics, weightlifting, and at least two years of strength training experience. They were all right footed (i.e., they all used their right foot to kick a ball) and physically active (at least two times per week over the last six months, at least 60 min per fitness session) and familiar with the movement patterns of the study (ability to perform eight consecutive repetitions of each pattern). Inclusion criteria also required no history of vestibular, orthopedic, or neurological disorders within the previous 12 months, as these could potentially affect movement patterns. During a familiarization session, an experienced examiner evaluated their ability to perform eight consecutive repetitions of two-legged squatting and standing hip abduction with proper technique (Table 1). This study was approved by the Bioethics Committee of the School of Physical Education and Sports Science, National and Kapodistrian University of Athens, Greece (approval ref. No. 1428/21/11/2022). Written informed consent was obtained from all participants in accordance with the principles of the Helsinki Declaration.

Table 1. List of key points checked by an experienced examiner in the familiarization session to verify the inclusion criteria of proper execution technique (maintenance of proper body form and body alignment as well as the avoidance of common mistakes).

Two-Legged Squatting	Standing Hip Abduction
• Stand with feet shoulder-width apart • Keep hands on hips throughout the movement • Bend knees and press hips back while keeping the upper body straight • Lower into a squat, ensuring not to go deeper than a 90-degree angle between the thigh and the shank • Press heels to the floor to return to the initial position	• Stand with feet hip-width apart • Place hands on hips (at mid-waist) • Keep the back and spine neutral throughout the movement, • Abduct the right lower extremity, after slightly raising the toes from the floor

2.2. Experimental Procedure

Task and Conditions. Participants performed the two-legged squatting and the standing hip abduction tasks while following a metronome stimulus set at their preferred tempo (2 trials in each task, 8 consecutive repetitions in each trial, with a 2 min rest between trials of the same task as well between tasks to avoid inducing fatigue [18]). Participants listened to the metronome sound and were instructed to start their movement when they felt ready, after a full eight-beat count. The number of trials was decided based on a previous study [19] suggesting that 2 trials are sufficient for reliable temporal measures in both the two-legged squatting and the standing hip abduction (intraclass correlation coefficient $\geq$ 0.75 [20], relative standard error of measurement $\leq$ 15%, that is within acceptable limits [21,22], and a coefficient of variation below 10% and rather closer to $\leq$5%), indicating the participants' capacity to time their movement with motor stability [23,24]. The metronome stimulus (Online Metronome: https://metronome-online.com/, accessed on 1 July 2024) consisted of a click sequence (click duration at 200 ms and frequency of the click sound at 440 Hz corresponding to the pitch of the musical note A4). Each trial consisted of 8 repetitions to align with the rhythmic structure of an eight-beat musical phrase, which is typical for the 32-count fitness music experts often used to accompany traditional exercise routines [25].

The preferred tempo estimation was conducted at the beginning of the session before data collection. Each participant performed eight consecutive repetitions of each exercise at their preferred tempo without a metronome. The duration of the total eight repetitions was timed in seconds and divided by the number of repetitions to calculate the single repetition duration in seconds. In continuance, the division of 60 s (1 min) by the single repetition duration provided the preferred tempo value used to set the beats per minute of the metronome stimulus, considering a 1:1 relationship between repetition and metronome beat.

2.3. Timing Data Recording—Instrumentation

The timing variables were extracted from the segmental angular velocity recorded with two inertial sensors (Xsens MTw Awinda (Xsens Technologies B.V., Enschede, The Netherlands), including triaxial accelerometer, gyroscope, and magnetometer, sampling at 100 Hz [26]) using the MT Manager software (Movella, Henderson, NV, USA) (links for the manual of the MT Manager software in Appendix A). All calibrated sensor readings are in the right-handed Cartesian coordinate system, which is body fixed to the device, described in the MTw Awinda User Manual and defined as the sensor coordinate system (link for the MTw Awinda User Manual in Appendix A). The inertial sensors (secured with elastic straps) were placed on the lower trunk (L5-S1) for the two-legged squatting and shank center of mass for the standing hip abduction (abducting lower extremity) (Appendix B Figure A1). The sensors were mounted securely on the participants while they maintained a neutral position (e.g., upright, not moving). Anatomical calibration of the sensors ensured that the x-axis angular velocity for the two-legged squatting represented the forward–backward motion of the trunk in the sagittal plane (rotation around the frontal horizontal axis), with forward leaning during the downward phase and backward leaning during the upward phase. For standing hip abduction, the z-axis angular velocity captured the outward–inward motion of the leg in the frontal plane (rotation around the sagittal horizontal axis), with outward motion during hip abduction and inward motion during hip adduction. To ensure the recording of a clear zero baseline, all participants were instructed to maintain a quiet standing period (about 2 s) before and after their movement initiation and termination, respectively. All timing variables were extracted from the angular velocity trajectories indicating the trunk inclination in the sagittal plane for the two-legged squatting and the shank inclination in the frontal plane for the standing hip abduction.

The metronome audio signal was recorded using the AcqKnowledge software version 5.6, sampling at 2000 Hz (link for AcqKnowledge manual in Appendix A). A laptop computer running Windows Media Player (v.12) served as the source for the metronome audio, which was heard through a JBL Go Essential Bluetooth speaker (Los Angeles, CA, USA) (set at a comfortable volume of 70 dB according to the guidelines of the World Health Organization [27]). One channel of a stereo-to-dual mono Y-cable directed the metronome audio signal to the speaker, while the other channel fed the signal into the Biopac MP150 data acquisition unit (link for Biopac MP150 unit in Appendix A). The metronome audio signal was recorded in synchronization with the angular velocity signal via an analog CBL100 cable connection of the Xsens MTw Awinda Station to the Biopac MP150 main unit (link for MT Manager manual in Appendix A). Thus, at the initiation of the metronome signal, a pulse generated through the AcqKnowledge software also triggered the MT Manager software to synchronize the initiation of the inertial sensor data recording.

2.4. Data Procession and Analysis

Preceding data extraction, all angular velocity signals were low-pass filtered (Butterworth filter, 4th order, cut-off frequency at 5 Hz, MATLAB R2022b, MathWorks, Inc., Natick, MA, USA) (link for the Butterworth filter design in Appendix A). The cut-off frequency was chosen based on the frequency power spectrum of all angular velocity signals, which indicated the highest signal intensity below 5 Hz.

2.4.1. Inter-Response Interval (IRI) Estimation

Both two-leg squatting and the standing hip abduction exhibited a periodic sinusoidal angular velocity trajectory (segmental inclination in the sagittal and the frontal plane for the two-leg squatting and the standing hip abduction, respectively), across all participants. This clear and consistent signal periodicity facilitated the accurate IRI detection through zero-crossing points marked with a circle index in Figure 1. The zero-crossing points were detected using the following MATLAB anonymous function:

```
zci = @(signal) find(signal(:).*circshift(signal(:), [−1 0]) <= 0);

zc = zci(signal);
```

This function identifies positions in the signal where a change in sign occurs between consecutive points, indicative of zero crossings. For more information on MATLAB anonymous functions, the find function, and the circshift, you can refer to the documentation links provided in Appendix A.

2.4.2. Metronome Beat Detection

To identify the onset of metronome beats, the metronome audio signal (Figure 2—top) was processed using MATLAB R2022b (MathWorks, Inc., Natick, MA, USA). Initially, a mel-spectrogram was computed to obtain a time–frequency representation of the signal (Figure 2—center). A mel-spectrogram is a spectrogram where the frequencies are converted to the mel scale (mel after the word melody), a perceptual scale of pitches judged by listeners to be equal in distance from one another. The mel scale was proposed by Stevens et al. [28] to overcome the fact that humans do not perceive frequencies on a linear scale, meaning that difference perception is better at lower (i.e., 500 to 1000 Hz) than at higher (i.e., 10,000 to 10,500 Hz) frequencies, despite that the distance between pairs of frequencies maybe being the same.

The MATLAB function used for the spectrogram computation was melSpectrogram (Sound, sample_rate), which returns three outputs, S, F, and T (S: the mel-spectrogram matrix, where each column represents a time frame and each row corresponds to a mel frequency band, F: a vector containing the center frequencies of the mel bandpass filters in Hertz (Hz), T: a vector providing the time indices for each time frame, measured in seconds) (link for the melSpectrogram function in Appendix A).

The mel-spectrogram function allowed for a detailed analysis of the signal's frequency components over time. The time frame value was set to 10 milliseconds (ms), which means that each time frame in the mel-spectrogram represents a 10 ms window of the audio signal. Thus, the vector T includes time indices spaced 10 ms apart, reflecting the time intervals at which the mel-spectrogram was computed. Subsequently, the energy of each time frame in the mel-spectrogram was calculated (Figure 2—bottom). The energy for each time frame is computed by summing the squared magnitudes of the mel-spectrogram values across all frequency bands. This step provides a measure of the signal's power at each time frame. In continuance, these energy values were used to identify the onset of the metronome beats. By applying a zero-crossing detection algorithm, the time point of each beat onset was determined (indicated with orange dots in Figure 2—bottom). The interval between two consecutive beat onsets defined the inter-stimulus interval (ISI).

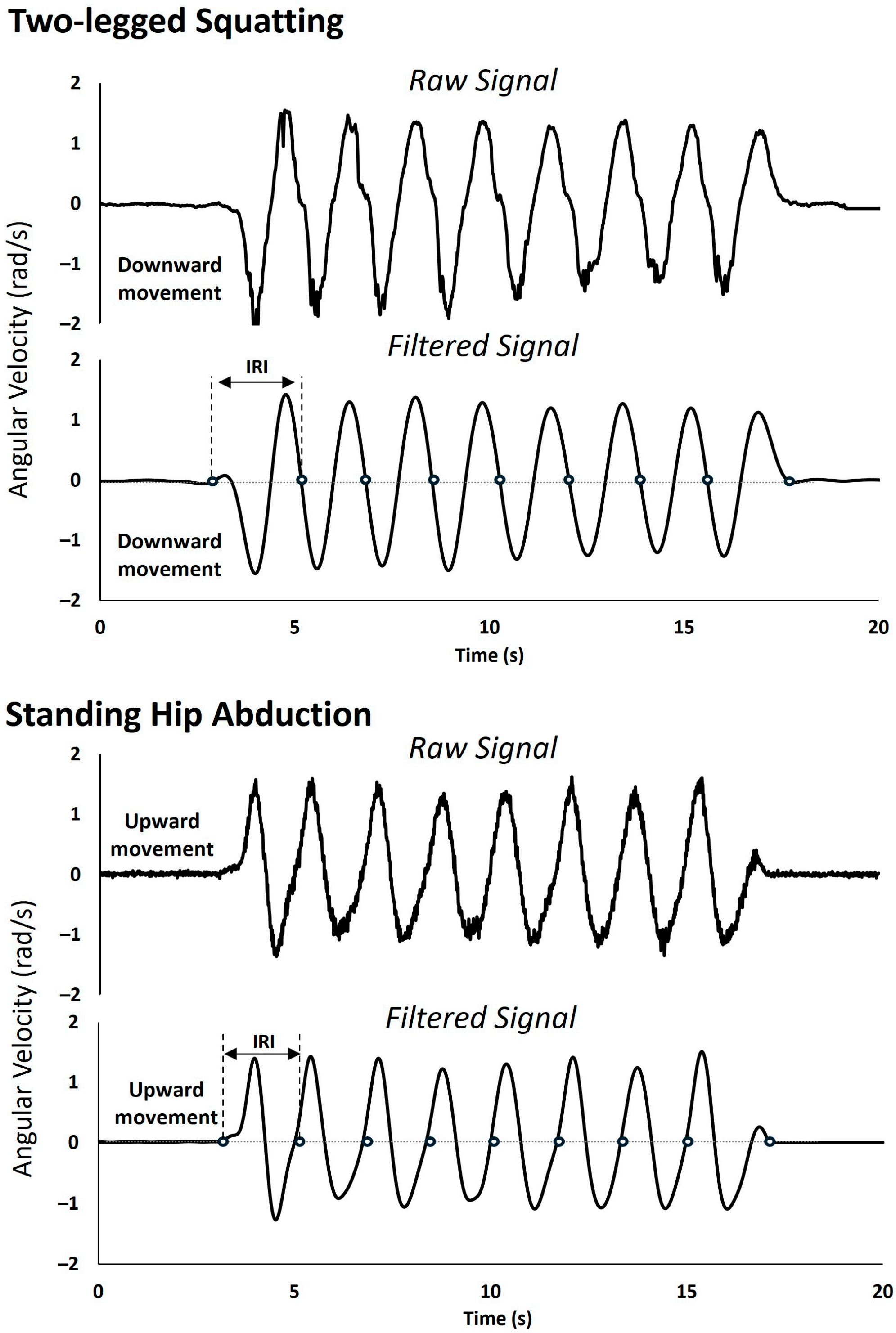

Figure 1. Exemplary angular velocity trajectories (raw and filtered ones) of the lower trunk sensor in two-legged squatting (**top**) and the shank in the standing hip abduction (**bottom**). The Inter Response Intervals (IRIs) (consecutive movement repetitions) were defined by the time intervals between consecutive zero-crossing points in the angular velocity trajectory (indicated with circle indices).

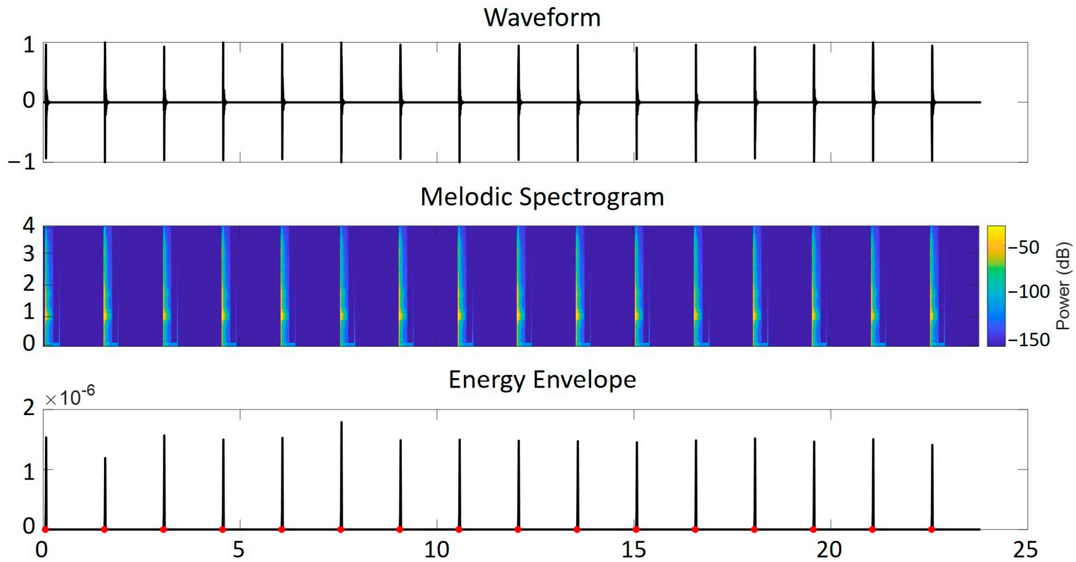

Figure 2. Metronome signal analysis. **Top**—waveform: time-domain representation of the audio signal. **Center**—melodic spectrogram: distribution of spectral energy over time. **Bottom**—energy envelope: audio signal with detected metronome beat onsets (orange dots).

2.4.3. Calculation of Timing Variables

For each exercise, the extracted variables aimed to assess the three aspects of movement timing, that is, entrainment, synchronization, and pace stability. To eliminate any potential transitional influence due to trial initiation or termination, the first and eighth repetitions were excluded from the analysis. Each participant's two-trials average was included in statistical analysis.

Entrainment Variables

Three variables were extracted for the entrainment timing aspect, that is, the IRI match, the IRI error, and the IRI error direction [4–6].

IRI Match: A ratio representing the match between the IRI and ISI intervals, whereas IRI is divided by ISI and then expressed as an ISI percentage (100% = ISI duration) (Equation (1)).

$$\text{IRI Match} = \frac{\text{IRI}}{\text{ISI}} \times 100 \tag{1}$$

IRI Error: A metric representing the ability to produce movements that align with the expected period of an external stimulus, such as a metronome beat interval, in terms of accuracy. For each repetition, the IRI error is calculated by measuring the difference between the IRI and ISI. In continuance, the absolute value of this time difference was expressed as a percentage of the ISI duration (100% = ISI duration) (Equation (2)).

$$\text{IRI Error} = \frac{|\text{IRI} - \text{ISI}|}{\text{ISI}} \times 100 \tag{2}$$

IRI Error Direction: To quantify the overall direction of the IRI error, the number (n) of negative and positive IRI errors was counted and expressed as a percentage (%) of the six repetitions (Equation (3)) (100% = 6). The IRI error direction provides insight into the participants' temporal control strategies and their entrainment to the metronome. In particular, the prevalence of negative IRI errors indicates that the participants speed up their movements, making the IRI shorter than the target ISI. Reversely, the positive IRI errors indicate that the participants slow down their movement, making the IRI longer than the cueing ISI.

$$\text{IRI Error Direction} = \frac{\text{n Negative(or n Positive) IRI Errors}}{6} \times 100 \quad (3)$$

Synchronization Variables

Two variables were extracted for the synchronization timing aspect (Figure 3), that ism the synchronization error and the synchronization error direction (negative or positive) [4–6], the latter offering insight into the synchronization mechanisms and the timing strategies.

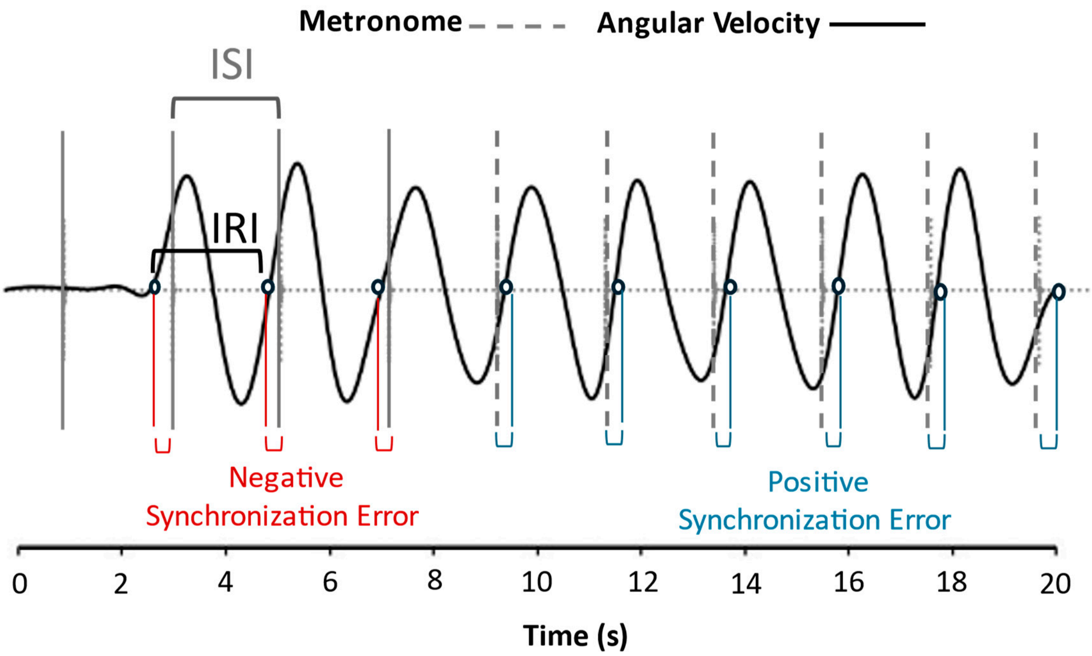

Figure 3. Exemplary iconic depiction of the synchronization variables calculation. The dashed vertical lines indicate the metronome beats onset and the white circles the zero-crossing time points in the angular velocity signal corresponding to the initial body position (the angular velocity trajectory depicts a hip abduction trial, where the angular velocity trajectory travels upwards as the lower leg is raised during abduction).

Synchronization Error: A metric representing the ability to produce a movement that is synchronized (in phase) with an expected external event (metronome beat) in terms of accuracy. For each repetition, the synchronization error was calculated by subtracting the time of the metronome beat onset from the time of the movement onset. In continuance, the absolute value of this time difference was expressed as a percentage of the ISI duration (100% = ISI duration) (Equation (4)).

$$\text{Synchronization Error} = \frac{|\text{Movement Onset} - \text{Beat Onset}|}{\text{ISI}} \times 100 \quad (4)$$

Synchronization Error Direction: To quantify the overall direction of synchronization error, the number (n) of negative and positive synchronization errors (movement onset early and late, respectively, relative to the metronome beat onset) was counted in each trial and expressed as a percentage of the total number of repetitions (100% = 6) (Equation (5)).

$$\text{Synchronization Error Direction} = \frac{\text{n negative(or n positive) synchronization errors}}{6} \times 100 \quad (5)$$

Pace Stability

IRI %CoV: Pace stability is an index of the within-subject timing variability and quantifies the consistency of movement timing within a sequence of repetitions [5,6]. A single variable was extracted for the pace stability metric, that is, the percentage IRI coefficient of variation (IRI %CoV), calculated by dividing the IRI SD by the mean IRI, and then multiplied by 100 and expressed as a percentage (%) (Equation (6)).

$$\text{IRI \%CoV} = \frac{\text{SD}_{\text{IRI}}}{\text{MEAN}_{\text{IRI}}} \times 100 \quad (6)$$

2.5. Statistical Analysis

Paired sample *t*-tests were conducted for a comparison of the timing variables between two-legged squatting and standing hip abduction. Effect sizes were calculated using Cohen's d, with thresholds defined as small (0.01), medium (0.06), and large ($\geq$0.14) [29]. The normality of data distribution was verified through histogram plots, Q-Q plots, Shapiro–Wilk tests, skewness, kurtosis, and z-scores. Despite minor deviations from normality, the overall data distribution was considered reasonably normal, with most z-scores falling within the $\pm$3 range [30]. All statistical analyses were conducted using IBM SPSS Statistics (v. 29.0) with a significance level of alpha $\leq$ 0.05.

3. Results

3.1. Inter-Response Interval (IRI)

Figure 4 illustrates the individual IRIs across the eight repetitions of the two-legged squatting and the standing hip abduction, for all 39 participants in Trial 1 and Trial 2 (Figure 4, top and center, respectively), as well as the two-trials average and standard deviation in each separate trial segment (Figure 4—bottom).

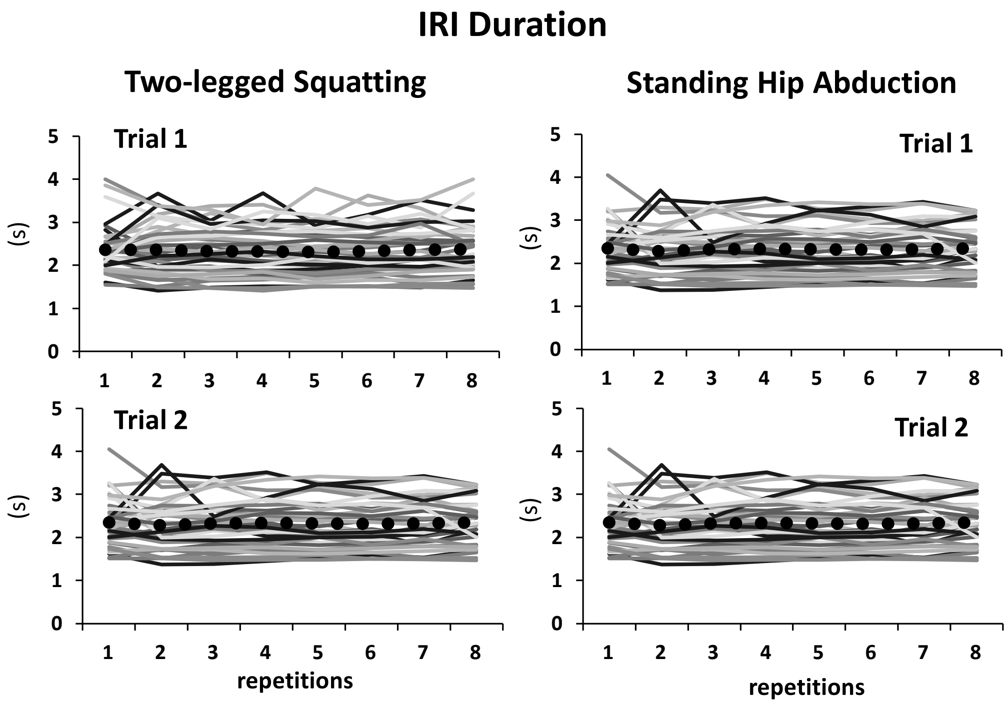

Figure 4. Individual inter-response interval (IRI) duration across all eight repetitions in the two-legged squatting (**left**) and the standing hip abduction (**right**) for all 39 participants in Trial 1 (**top**) and Trial 2 (**bottom**). Each line represents the IRI durations of a single participant, while the black circles indicate the averaged IRI duration across the 39 participants.

Across all three trial segments, the IRI was significantly shorter in the standing hip abduction than the two-legged squatting ($p < 0.01$ for all) (Figure 4—top).

3.2. Entrainment

The results indicated no significant differences in IRI match between the two-legged squatting and the standing hip abduction (t = 1.04, $p = 0.306$, Cohen's d = 0.17) (Figure 5). The IRI error was about 50% greater in standing hip abduction (t = −4.41, $p < 0.001$, Cohen's d = 0.71) (Figure 5). However, the IRI error direction did not yield a significant difference between the two exercises, neither for the negative (t = −0.46, $p = 0.646$, Cohen's d = −0.07), nor for the positive ones (t = 0.12, $p = 0.909$, Cohen's d = 0.02), (Figure 5).

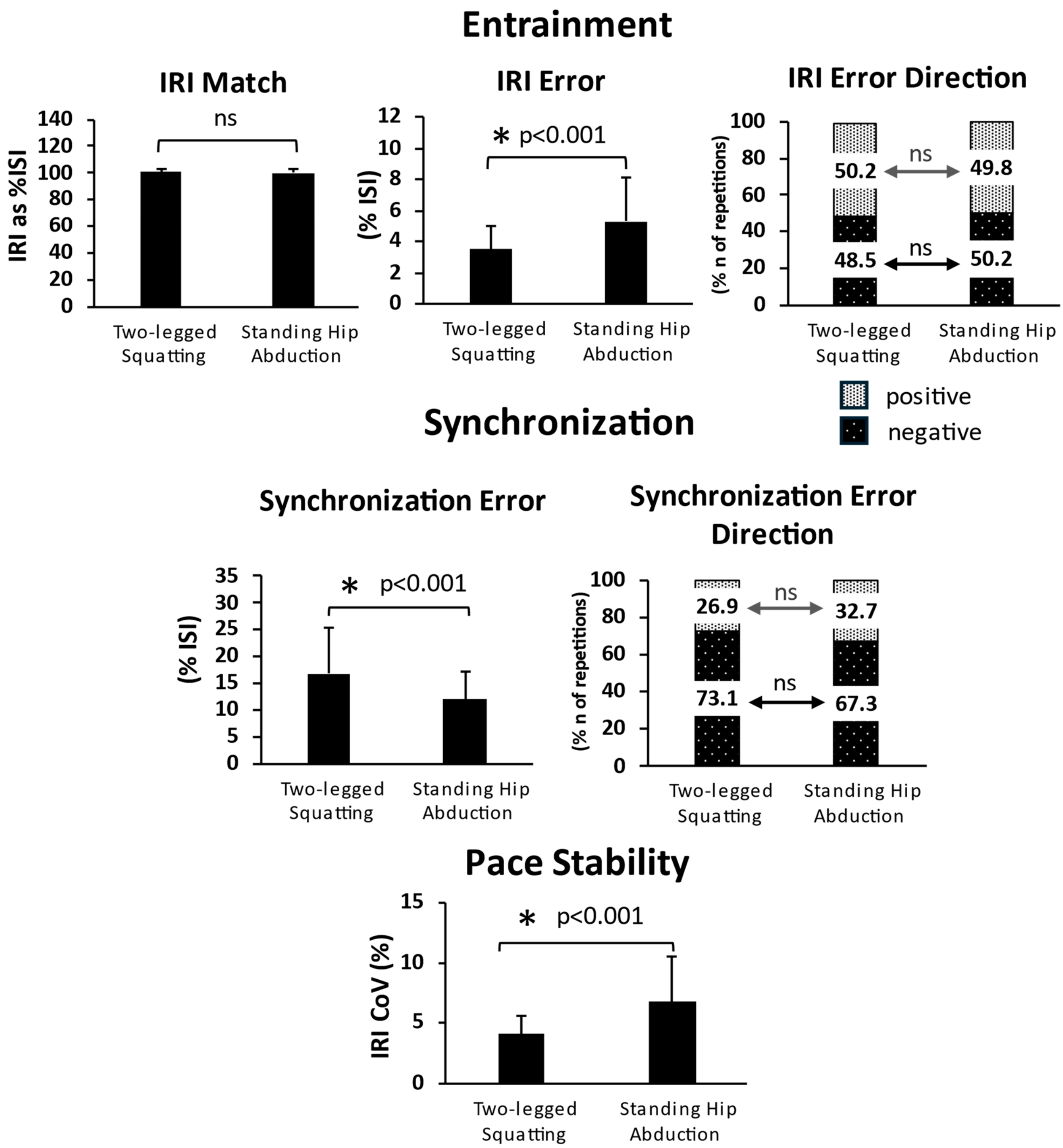

Figure 5. Mean and standard deviation of entrainment (**top**), synchronization (**center**), and pace stability (**bottom**) variables, in two-legged squatting and standing hip abduction. IRI Match: Ratio of

inter-response interval (IRI) to the inter-stimulus interval (ISI). IRI error: Difference between IRI and ISI (% of ISI duration). IRI Error Direction: Percentage of negative and positive IRI Errors (100% = 6 IRIs) (black: negative, grey: positive). Synchronization Error: Temporal difference between movement onset and metronome beat onset (% of ISI duration). Synchronization Error Direction: Percentage of negative and positive asynchronies (100% = 6 IRIs) (black: negative, grey: positive). IRI %COV: IRI coefficient of variation expressed as a percentage. * Significant difference at $p < 0.05$, ns: non-significant difference at $p > 0.05$).

3.3. Synchronization

Participants demonstrated an about 30% significantly higher synchronization error during two-legged squatting than standing hip abduction (t = 3.11, p = 0.004, Cohen's d = 0.50) (Figure 5). Regarding the synchronization error direction, neither the negative (t = 0.92, p = 0.365, Cohen's d = 0.15) nor the positive (t = −0.92, p = 0.365, Cohen's d = −0.15) ones differed between the two exercises (Figure 5).

3.4. Pace Stability

The standing hip abduction exhibited significantly less pace stability, as indicated by its greater IRI %CoV (about 2.6 percentage units greater than two-legged squatting) (t = −4.77, $p < 0.001$, Cohen's d = −0.76) (Figure 5).

4. Discussion

This study aimed to investigate the movement timing beyond the tapping paradigm, employing two large-scale movements commonly performed in physical fitness or rehabilitation modalities, with varying inherent balance threats: the two-legged squatting (low balance threat) and the standing hip abduction (higher balance threat). This study focused on three aspects of movement timing, that is, entrainment, synchronization, and pace stability. Our incentive was that, although the finger-tapping paradigm has provided valuable insights into movement control, it simplifies movement mechanics by minimizing force, restricting motion, and relying on a clear surface contact endpoint. Consequently, finger tapping cannot fully capture the complexity of larger-scale movements, where distinct strategies naturally emerge, such as timed multi-segmental (i.e., two-legged squatting) and single-segment (i.e., standing hip abduction) body movements often employed in physical fitness or rehabilitative modalities.

Our findings revealed that while participants demonstrated similar overall entrainment in both the two-legged squatting and the hip abduction (evidenced in their non-significantly different IRI match), significant differences emerged in timing metric manifestations. Specifically, the movement of greater balance threat (standing hip abduction) demonstrated more accurate timing alignment with metronome beats (as evidenced by its smaller synchronization error) but lower entrainment accuracy and movement timing consistency (as evidenced by its greater IRI error and lower pace stability).

The shorter IRI in the standing hip abduction than the two-legged squatting was rationally expected due to its lower inertial load [31] and its balance loss vulnerability [32]. Previous research has consistently shown that higher inertial loads are linked to slower movement tempos, while lower inertial loads lead to faster-preferred tempos [31,33]. While our study did not directly manipulate inertial load, the observed difference in IRIs aligns with this established principle. Also, in situations requiring rapid stabilization, individuals tend to minimize the time spent in a vulnerable position [31].

Entrainment refers to the general phenomenon of matching body movement frequency to the pace of a regular cue, such as metronome or music beats [7], without necessarily synchronizing a particular motor element to a discrete beat [5]. Previous research established the entrainment phenomenon on the simple task of finger tapping [4,6,8,34–36]. However, there is some evidence that simple tasks like finger tapping may not fully capture the motor complexity of a larger-scale movement such as stepping in place [5,15]. The similar IRI match values between the two exercises indicate that, regardless of the greater movement complexity in two-legged squatting and the greater balance demands in standing hip abduction, participants were able to align their movement frequency with the external pacing cue. Larger-scale movements, such as the multi-segmental or single-segment body movements used in physical fitness and rehabilitation, involve distinct strategies and additional demands that simpler and smaller movements do not address [2,11]. Our results challenge the conventional focus on the simple finger-tapping paradigm, underscoring the flexibility of the human motor system in entraining to rhythmic cues, even in more challenging contexts [2,5,6,11]. One could argue that the IRI match should anyways be expected, as the metronome tempo was already set at their preferred frequency. This is a reasonable assumption; however, it is notable that even in entrainment to a metronome stimulus at preferred tempo, the balance threat appears to influence specific timing manifestations, such as the timing consistency.

Entrainment accuracy, examined through the IRI error, was lower during the movement under greater balance threat, that is, the standing hip abduction (as expressed with a higher IRI error). This finding most likely highlights the trade-off between stability and accurate timing under balance challenges, even at the preferred tempo entrainment. It appears that when required to follow an auditory pacing cue, the individuals prioritize performance safety, and the focus on maintaining balance may come at the cost of timing accuracy. This observation is consistent with Wright and coworkers [15], who report smaller temporal corrections in their more complex motor task of stepping in place than the simpler finger tapping, suggesting that the central nervous system may prioritize stability over timing accuracy. Chen and coworkers [16] also found that their more complex motor task of stepping in place exhibited slower compensation for timing shifts than their simpler task of heel tapping. Similarly, Gabbard and Hart [17] reported fewer taps and reduced performance during single-leg standing compared to seated finger tapping. While Gabbard and Hart [17] did not specifically measure accuracy, their findings suggest that balance challenges, such as single-leg standing, negatively affect performance, supporting the idea that under conditions of greater balance threat, motor tasks become more challenging, which could potentially lead to reduced accuracy in timed movements.

Synchronization, unlike entrainment, requires the accurate alignment of self-initiated movements with specific points in an external pacing source. This process involves sophisticated sensorimotor adjustments and error correction mechanisms [8]. Synchronization accuracy is measured by the synchronization error metric, which quantifies the temporal discrepancy between the stimulus pacing event (e.g., auditory beat onset) and the movement event (e.g., movement onset) [4,6,8,10]. Unexpectedly, our findings revealed lower synchronization accuracy (higher synchronization error) during the movement of the reduced balance threat (two-legged squatting) than the one with an inherently greater balance threat (standing hip abduction). This finding contradicts previous results on finger/foot tapping versus stepping in place, where the task of higher balance demands led to worse synchronization accuracy [16]. In our study, the worse synchronization accuracy in the movement under a lower balance threat most likely suggests that factors beyond balance, such as movement complexity and scale, may play a crucial role in accurate timing alignment with external cues [2,8,13].

In an effort to maintain synchronization, the increased complexity of two-legged squatting may introduce greater functional variability [37], expressing the "fine motor tuning" to correct minor temporal deviations between the movement and the beat onset. This aligns with Wright and coworkers [15], who reported that complex movements lead to less accurate phase adjustments than simpler tasks. The automatic and largely unconscious phase correction process may have been more challenging during two-legged squatting due to larger muscle groups and multiple joint engagements [2,8,15,38]. Thus, despite the inherently lower balance threat, the necessity of timed multi-segmental coordination may produce functional variability that leads to an execution variability that ultimately allows for more accurate synchronization.

In timed movements, pace stability is a metric of execution timing variability [39] that evaluates the consistency of movement timing without explicit reference to a cue, and it is quantified by the IRI coefficient of variance [11,12]. Overall, in both exercises, IRI %CoV was below 10% and rather closer to ≤5%, indicating the participants' capacity to time their movement with motor stability [23,24]. However, the standing hip abduction exhibited a significantly higher IRI %CoV than the two-legged squatting, highlighting a notable difficulty to maintain a consistent pace when balance is inherently threatened due to single-leg standing. This finding is consistent with previous research demonstrating that tasks with greater balance challenges tend to introduce more timing variability [2,16]. It also supports the idea that pace stability is influenced by the complexity of the movement, with more complex or more challenging movements exhibiting greater timing variability due to the increased demands on balancing motor control [15]. Due to its inherent balance threat, the standing hip abduction most likely also involves greater proprioceptive demands. In the absence of external spatial feedback, timing variability may be exacerbated due to increased reliance on internal sensory information [2]. Thus, in standing hip abduction, a balance threat interference may interfere by leading to a greater reliance on proprioceptive and cognitive information to achieve a successfully timed movement, while at the same time mitigating the balance loss to ensure the safety of performance [40].

The direction of the IRI error, as well as the direction of the synchronization error, did not differ between the two exercises, suggesting that the balance threat did not bias the direction of the timing errors. Participants showed a consistent prevalence of both overestimation and underestimation of movement intervals, as well as of earlier and later movement onsets, regardless of the greater balance threat in the standing hip abduction. This indicates that while balance challenges impact overall timing accuracy, they do not necessarily alter the internal process of timing adjustments [41]. According to the Adaptation and Anticipation Model (ADAM) of sensorimotor synchronization, error correction mechanisms are essential for maintaining temporal alignment and coping with timing variability [41]. The model highlights how phase and period correction processes (operating both reactively and predictively) help adapt to timing changes without systematically altering the direction of errors [42,43]. The observed consistency of these measures under varying balance conditions underscores the resilience of the sensorimotor synchronization mechanisms, as well as their flexible adaptation to varying demands [43]. It appears that, despite balance challenges impacting the timing accuracy, the underlying error correction mechanisms remain robust and maintain their efficacy across different contexts [41,42].

This study provides timed-movement insights beyond the traditional finger-tapping paradigm by examining larger-scale, multi-segmental (two-legged squatting) and single-segmental (standing hip abduction) movements, with the latter introducing a higher balance threat. The justification of our study rationale is reflected in the increased magnitude of the variables expressing the aspects of movement timing compared to those in typical finger-tapping studies. For the movements examined in our study, entrainment was succeeded with an IRI error at 3.5% for two-legged squatting and at 5.3% for standing hip abduction, indicating an increase of 3.5- to 5.3-times compared to the 1% IRI error typically reported in finger-tapping studies [5,6]. Synchronization was also succeeded with a greater synchronization error that averaged 16.8% in two-legged squatting, indicating an increase of 1.5- to 2-times greater than the 8–11% observed in finger tapping [5,6]. In standing hip abduction, the synchronization error averaged 11.9%, which was also higher than the values reported for finger tapping but rather closer to the upper limit of the 8–11% finger-tapping range [5,6].

Motor timing is influenced not only by task complexity but also by the speed constraints inherent to the task. Motor control as well as behavioral studies indicate that movement timing is constrained by both the motor system's capacity to move rapidly [5,6] and the cognitive system's ability to maintain precise control [13,44], with predictive timing becoming increasingly difficult as the tempo either speeds up or slows down. Furthermore, when an auditory stimulus is provided under a threatening situation, the perceived capability for preferred motor action appears to be affected [45]. The role of tempo typically applies to tempo outside the preferred one; however, one could speculate that the inherently slow natural tempo of the more complex movements examined in the present study (ISI at 2.33 s for two-leg squatting and 1.91 s for hip abduction) may underlie the timing differences compared to the faster, simpler finger-tapping task (ISI from 400 to 700 ms) [5,6,8].

Not including a finger-tapping task in our study could be considered a limitation as it does not allow for a direct comparison with the movements employed, thus not allowing us to fully capture the nuances of timing accuracy in the transition from simpler to more complex tasks. However, the numerically well-established timing metrics and manifestations of the finger-tapping paradigm allow for a safe indirect comparison. Future research could focus on the inclusion of movements that vary widely in terms of movement complexity and inherent or external balance threat. Also, emerging technological advancements that have been shown to capture synchronization issues in coupled oscillators such as machine learning [46] could most likely enhance the detection of synchronization errors and improve timing accuracy in complex motor tasks under varying balance conditions.

The findings have significant practical implications for sports, fitness, and rehabilitation. Rhythmic auditory cues can enhance timing and coordination in complex movements like squatting and hip abduction. Coaches can use these insights to design training programs that address timing and stability challenges, particularly in exercises with high balance demands. In rehabilitation, incorporating rhythmic cues can support motor control and stability in patients recovering from injuries or dealing with balance issues, allowing therapists to create progressively challenging exercises. Understanding how balance and movement complexity affect rhythmic cue effectiveness can lead to more effective training and rehabilitation strategies.

In conclusion, this study highlights the complex interplay between movement timing, balance challenges, and movement complexity in response to a metronomic stimulus. While entrainment to rhythmic cues was achieved in both the lower and higher balance threat movements, timing accuracy and pace stability varied. In the higher balance threat movement (standing hip abduction), reduced entrainment accuracy and pace stability suggest that balance demands take precedence over timing. Conversely, the complexity of two-legged squatting introduced variability that impaired the synchronization accuracy. These findings emphasize the importance of considering both balance and movement complexity when designing training and rehabilitation programs employing timed movements. Future research should include a wider range of tasks in terms of movement complexity and balance threat as well as explore additional factors like sensory feedback to further understand timing accuracy in dynamic environments. Also, emerging technological advancements such as machine learning could most likely provide more comprehensive insights about the timing accuracy of complex motor tasks under varying balance conditions, timed to diverse acoustic stimuli beyond that of a metronome.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The datasets presented in this article are not readily available because the data are part of an ongoing study. Requests to access the datasets should be directed to the corresponding author.

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Appendix A

Table A1. Software, hardware and MATLAB function * links.

Manuscript Section	Software—Hardware	Link
2.3. Timing Data Recording—Instrumentation.	MT Manager software (Movella, Henderson, NV, USA)	https://www.xsens.com/hubfs/Downloads/usermanual/MTi_usermanual.pdf
	MTw Awinda User Manual	https://www.xsens.com/hubfs/Downloads/Manuals/MTw_Awinda_User_Manual.pdf
	AcqKnowledge software version 5.6.	https://www.biopac.com/demo/acqknowledge-5-demo/
	Biopac MP150 data acquisition unit	https://www.biopac.com/wp-content/uploads/MP150-Systems.pdf
	Xsens MTw Awinda Station Connection to the Biopac MP150 main unit	https://www.xsens.com/hubfs/Downloads/usermanual/MT_Manager_user_manual.pdf
2.4. Data Procession and Analysis	Low pass 4th order Butterworth filter, cut-off frequency at 5 Hz	https://www.mathworks.com/help/signal/ref/butter.html
2.4.1. Inter Response Intervals (IRIs) Estimation	Anonymous Functions	https://www.mathworks.com/help/matlab/matlab_prog/anonymous-functions.html
	find function	https://www.mathworks.com/help/matlab/ref/find.html
	circshift	https://www.mathworks.com/help/matlab/ref/circshift.html
2.4.2. Metronome beat detection	melSpectrogram (Sound, sample_rate) function	https://www.mathworks.com/help/audio/ref/melspectrogram.html

* MATLAB R2022b, MathWorks, Inc., Natick, MA, USA, all links assessed on 6 July 2024.

Appendix B

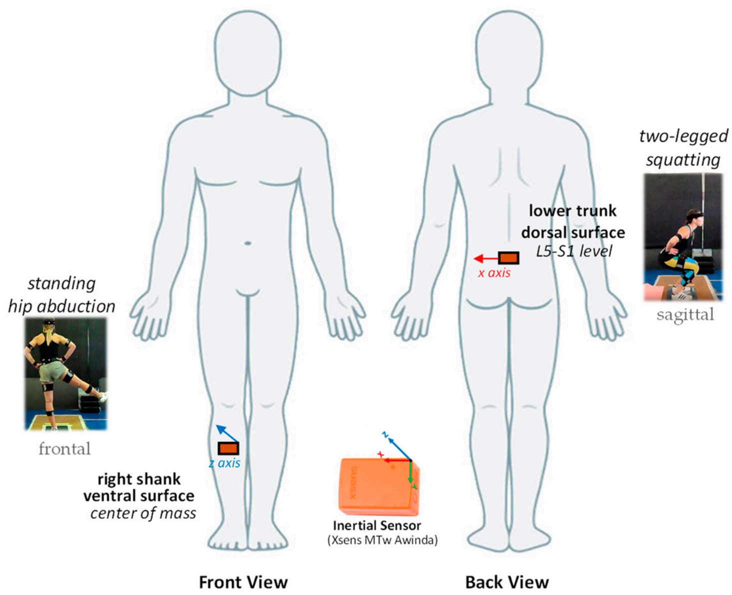

Figure A1. The body position where each one of the two inertial sensors used in this study was placed, as well as the exercise that is associated with each sensor (the plane of motion of each exercise is noted). The Xsens inertial sensor and its fixed coordinate system (x, y, and z axes) are also shown.

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