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A state-of-the-art review on badminton lunge attributes

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ABSTRACT

Good badminton lunge skills have been quantitatively described using biomechanical attributes at both static and dynamic phases. The measurement of badminton lunge attributes has often been complicated by various experimental protocols used. No review article has considered or critically reviewed the attributes that align with badminton lunge performance. This paper, hence, presents a review of badminton lunge postures governed by various determinant attributes. This review was performed by involving a number of relevant search engines. A total of 21 articles that fulfilled the predefined inclusion criteria were analysed. The lunge determinant attributes, such as time, lunge distance, plantar, ground reaction force, joint, dynamic balance and muscle attributes, had been examined. Contradictory findings in the dynamic balance attributes, specifically the relative displacement between the centre of mass and the centre of pressure, are presented in this paper. The findings showed that time, lunge distance and ground reaction force determined lunge performance. On the other hand, plantar, joint, dynamic balance and muscle attributes appeared useful in minimising injuries to ensure efficient lunge performance.

1. Introduction

Badminton is the world's fastest racket sport, popularly contested in tournaments [1]. The long history of badminton game analysis has shown the increasing emphasis on performance skill optimisation, which reduces the chances of fatigue and potential injury. Research studies have also been carried out on badminton motion perspectives, including smash, clear, drop shot and lunge [2–4]. Where badminton injuries are concerned, researchers have focused on the lower body extremities [5–9] and the upper body joint motions [10–12].

A good badminton lunge enables fast and efficient movement, which is the fundamental requirement in badminton matches. Based on the lunge time reported in research studies [13–15], good lunges are completed within a few seconds, approximately 1.11–2.20 s. Major research studies have been devoted to examining kinetics and kinematics attributes to optimise players' lunge performance [16]. Studies that have commonly focused on attributes that affected badminton lunge performance have also included time, lunge distance, plantar, ground reaction force, joint, dynamic balance and muscle attributes. However, the effects of the main attributes on badminton lunge performance seem unclear and demands further investigation [16]. To the best of the authors' knowledge, no review article has comprehensively compiled and compared the reported attributes associated with badminton lunge analysis. To this end, this paper presents the potential study determinants and several knowledge gaps in badminton lunge analysis.

A systematic search strategy was employed in this study to retrieve research articles pertaining to badminton lunge from Scopus, ScienceDirect and Google Scholar databases. The primary goal was to synthesise and review research findings concerning lunge attributes. The existing experimental protocols, as well as lunge determinant findings discrepancies, are elaborated in the following sections.

2. Methodology

The search strategy that involved Scopus, ScienceDirect and Google Scholar databases was performed from the beginning date of the databases until the end of September 2018 (see Table 1). Fig. 1 illustrates the search strategy framework in selecting badminton lunge articles for review. The search for articles was conducted by using several keywords, such as “badminton” and “lunge” or “footwork”, particularly in screening for the abstract section in Scopus and ScienceDirect. Google Scholar, however, had a different search function, as portrayed in Table 1. For example, “intitle:lunge” and “badminton” returned articles that had “lunge” in the title (articles that focused on lunge motions) and “badminton” in any part of the articles. It should be noted that the keyword “badminton” was not searched for within the title to avoid overfitting.

Article links were assessed at the preliminary search stage to discard

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Table 1
Specification of the search strategy in Scopus, ScienceDirect and Google Scholar databases.

Database	Search strategy
Scopus	TITLE-ABS-KEY (badminton) AND (TITLE-ABS-KEY (lunge*) OR TITLE-ABS-KEY (lunging) OR TITLE-ABS-KEY (footwork*))
ScienceDirect	Title, abstract, keywords: badminton AND (lunge* OR lunging OR footwork*)
Google Scholar	intitle:lunge OR intitle:lunges OR intitle:lunged OR intitle:lunging OR intitle:step OR intitle:steps OR intitle:footwork OR intitle:footworks badminton lunge OR lunges OR lunged OR lunging

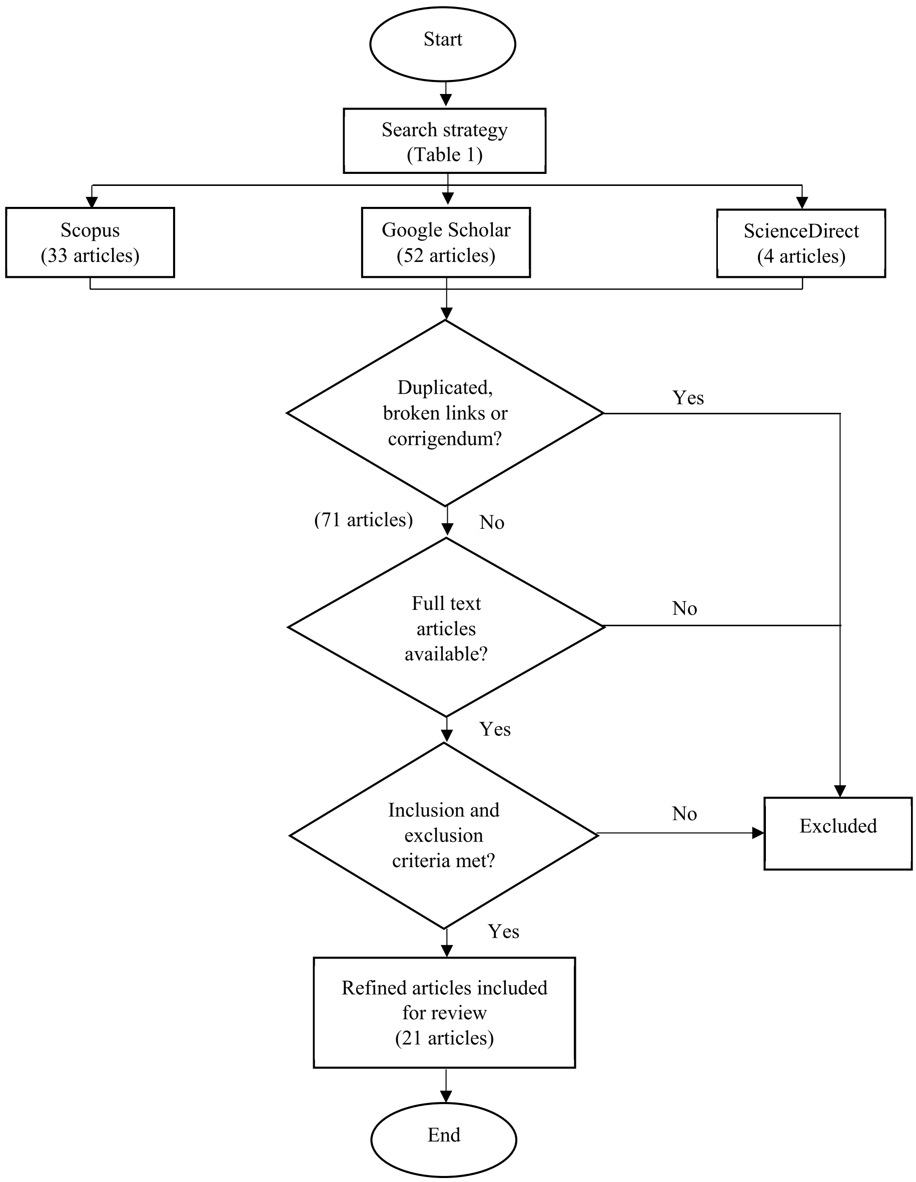

Fig. 1. Flowchart of review search strategy.

duplicated links and corrigendum, thus resulting in 71 articles. After retrieving available full-text articles, the article selection was further refined based on the following inclusion and exclusion criteria:

- Inclusion criteria: Participants performing badminton lunge motions (with lunge attributes measured) for game simulations.
- Exclusion criteria: Articles in non-English languages without available English translation, lunge studies for other sports, badminton studies without lunge experiments, and review articles.

The refining process returned 21 articles for review (see Fig. 1).

3. Study attributes

Badminton lunge patterns were studied from various perspectives, inclusive of kinematics and kinetics effects. Kinematics attributes, such as time and velocity, have been commonly investigated in players' performance analysis, whereas kinetics attributes, such as ground reaction force and plantar pressure, have given insight into injury mitigation.

The major attributes reviewed in this paper were the commonly analysed attributes in association with badminton lunges, including time, lunge distance, plantar, ground reaction force, joint, dynamic balance and muscles (see Fig. 2).

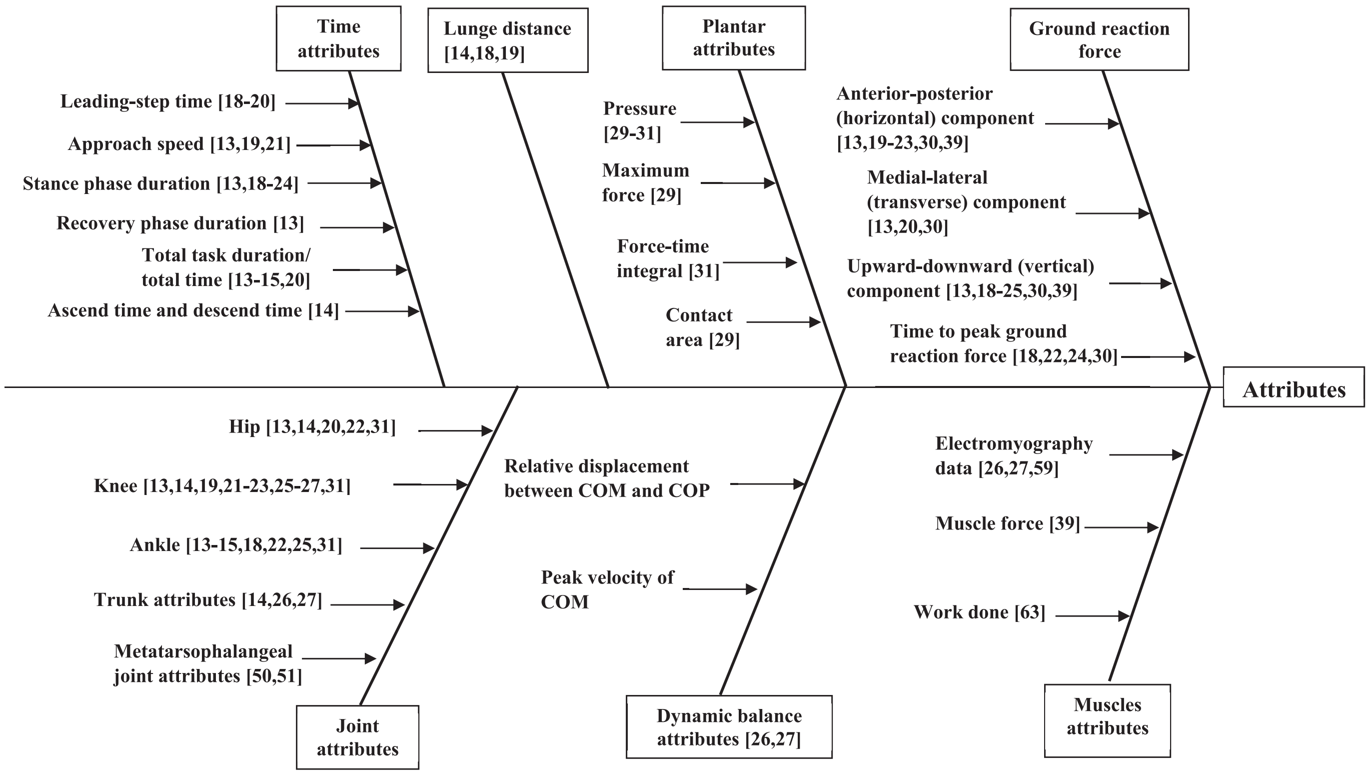

Fig. 2. Study attributes in the badminton lunge.

3.1. Time attribute

Badminton is the world's fastest racket sport, and players have limited time to perform specific movements [2,17]. The time attribute is essential in evaluating players' lunge movements in terms of their ability to perform lunges to execute a shot and then return to the base position quickly. Common badminton lunge experiments have involved the subject performing either one or multiple-step lunges from the starting position, with the leading (dominant)* foot landing on a force plate before hitting the shuttlecock, followed by sequential foot lifting and moving back to the starting position. Different articles have used different terms referring to the same time attribute, as categorised in Table 2.

3.1.1. Moving forward

As badminton players move forward to hit the shuttlecock, several quantitative time attributes, including leading-step time, performance time and approaching speed, are deemed as important. Lin et al. [18] compared the leading-step time among players wearing shoes of different thicknesses, whereas Lam et al. [19] considered the approaching time in players with shoes of different heel shapes to compare between elite and intermediate players (two-way repeated measures analysis of variance [ANOVA]). No significant difference was reported in both articles. The articles deduced that differently designed shoes had no significant effect on the step-forward time [18,19].

Lin et al. [20] compared step-forward duration time and performance time in two-step and three-step forward lunges at pre-specified lunge distances. There had been significantly shorter step-forward duration time and performance time reported for three-step lunges,

Table 2
Time attributes description.

Attribute	Description
Leading-step time/approaching time/step-forward duration time	Time taken from when the player moves from the starting point to when the heel of the leading (dominant)[a] foot lands on the force plate.
Stance phase duration/foot contact time/ground contact time/landing duration time	Time taken from when the heel of the leading (dominant)[a] foot lands on the force plate to when the foot fully lifts off from the force plate.
Recovery phase duration	Time taken from when the leading (dominant)[a] foot fully lifts off from the force plate and then returns to the starting point.
Total task duration [13,14]	Time taken from when the player moves from the starting point, lands on the force plate and then returns to the starting point.
Descend time	Time taken from when the player moves from the starting point to when the leading (dominant)[a] foot fully lands on the force plate.
Ascend time	Time taken from when the leading (dominant)[a] foot fully lands on the force plate and then returns to the starting point.
Performance time/movement time	Time taken from when the player moves from the starting point to when the player hits the shuttlecock.
Total time [20]	Time taken from when the player moves from the starting point to when the leading (dominant)[a] foot fully lifts off from the force plate.

[a] Lunges were performed with dominant foot in all articles except for Nadzalan et al. [14,24,59], in which the badminton players were required to lunge sequentially with dominant and non-dominant foot.

when compared to two-step forward lunges. Their findings suggested that players should put greater emphasis on three-step lunge method to perform quicker lunges. Nonetheless, it has remained unknown if similar findings can be obtained for varied lunge distances.

Kuntze et al. [13] and Lam et al. [19,21] studied the aspect of approaching speed, which was derived from approaching time, as given in Equation (1):

$$Approaching\ speed = \frac{Lunge\ distance}{Approaching\ time} \tag{1}$$

It appears that leading-step time, performance time and approaching speed reflect players' ability to perform lunges to hit the shuttlecock quickly. Future studies may assess leading-step time, performance time and approaching speed by considering a range of lunge distances to evaluate performance.

3.1.2. Stance phase

The stance phase is defined as the duration from when the player's foot contacts the ground at the final footstep before hitting the shuttlecock to when the foot fully lifts off from the ground to return to the base position. Ground reaction force, joint kinematics, dynamic balance and muscle attributes are associated with stance phase. Therefore, the stance phase is the focus of badminton biomechanics.

Although the stance phase has been mentioned in common lunge strategies, the stance phase duration has only been statistically analysed in some articles [13,18–24]. Further research may embed statistical significance tests on the stance phase duration, along with other time attributes, to gain insight into lunge performance.

The beginning and the end of the stance phase were determined from the cut-off magnitude of the vertical ground reaction force (see Table 2). This metric functioned as a threshold to determine the foot contact time duration. Different cut-off magnitudes have been reported in the past: 10 N in Lam et al. [19,21], 15 N in Kuntze et al. [13] and 20 N in Fu et al. [25]. Meanwhile, stance phase breakdowns have also been reported in various other studies, as shown in Table 3.

3.1.3. Recovery

During the recovery phase, after hitting the shuttlecock, players move back to the standby position (base position) to prepare for the next movement. The study by Kuntze et al. [13] seems to be the only article that has reported recovery phase duration. The authors found that the hop lunge had a significantly shorter recovery phase duration than that for step-in lunge. More studies are required to probe into recovery phase duration to assess players' ability to return to the base position in preparation for the next move.

3.1.4. Total task duration

Total task duration reflects the time taken when players lunge to execute a shot and then return to the base position. Stance phase duration has been more commonly reported (eight articles) [13,18–24], but only four articles [13–15,20] have reported the total task duration. Kuntze et al. [13] determined the total task duration as the sum of approaching time, stance phase duration and recovery phase duration. However, no significant variance has been reported for total task duration between kick, step-in and hop lunges [13].

Lin et al. [20] calculated the total time as the sum of step-forward duration time and landing duration time (see Table 2). Nadzalan et al. [14] described descend time, ascend time and total time taken for lunge movement (see Table 2). The total time taken was the sum of descend time and ascend time, which was equivalent to the total task duration mentioned in Kuntze et al. [13]. The descend time, ascend time and total time taken were significantly faster for the dominant limb, as compared to the non-dominant limb [14].

The time taken (from hitting the shuttlecock and then returning to the starting point) for a lunge in each of the six directions (right-forward, left-forward, right-lateral, left-lateral, right-backward and left-backward) and the total time taken for the six consecutive lunges were reported in Park et al. [15].

Future studies may need to look into leading-step time, stance phase duration, recovery phase duration and total task duration as assessments of players' lunging ability to hit the shuttlecock and then return to the base position in time.

3.2. Lunge distance

The definition of lunge distance in the reviewed articles is the distance travelled from where the player began to lunge until the last footstep before hitting the shuttlecock. This attribute indirectly reflects the players' lunge performance, i.e. the ability to perform a quick lunge at a specific distance to hit the shuttlecock.

Several papers have linked lunge distance with leg length of the badminton players (see Equation (2)). For example, the lunge distance by scale factors of leg length has been considered in Kuntze et al. [13], Huang et al. [26] and Lin et al. [27].

$$Lunge\ distance = k \times leg\ length \tag{2}$$

where:

$k = 1.5$ [13], 2.5 and 3 [26,27].

Leg length has been defined as the vertical distance between the anterior superior iliac spine (ASIS) and the ground in Kuntze et al. [13]. The authors specified the lunge distance as 1.5 times leg length. This distance is deemed as the largest distance for successful recovery from kick, hop and step-in lunges [13]. On the other hand, lunge distance was 2.5 times leg length for forward diagonal lunge and 3.0 times for backward diagonal lunge by individual players, as reported in Huang et al. [26] and Lin et al. [27].

Nevertheless, it was unspecified in Huang et al. [26] and Lin et al. [27] if the leg length measured refers to the true leg length or the apparent leg length. The leg length metric should be defined clearly, since there are different methods to measure leg length. For example, the true leg length can be measured as the distance between ASIS and medial malleolus, or the distance between pelvis and bottom of the heel. Additionally, the apparent leg length may also be measured as the distance from the umbilicus to the medial malleolus [28].

Apart from the above metrics, the players' maximal lunge capabilities can be assessed by their maximum lunge distance and lunge speed prior to the experiment to simulate a real badminton match. The lunge distance achieved by individual players was recorded as the maximal lunge distance to be performed for biomechanics assessment. The one-step maximal lunge has been commonly reported, in which the badminton player lunges at a predefined consistent lunge distance [19,22,23,29].

Table 3
Subcategorization of stance phase used in articles.

Categorisation	Article
Initial impact peak (heel strike transient), secondary impact peak (impact loading), amortisation, weight acceptance (loading), drive-off	Lees and Hurley [39], Kuntze et al. [13]
Initial impact peak, secondary impact peak, weight acceptance, drive-off	Fu et al. [25]
Hitting phase, recovery phase	Huang et al. [26], Lin et al. [27]
Breaking impulse duration, propulsive impulse duration	Lin et al. [18], Lam et al. [21]

While most studies have considered one-step lunges, the three-step maximal lunge was examined in Hong et al. [30]. To date, the number of lunge steps for an optimal lunge performance has not been determined. Lin et al. [20] reported that the three-step lunge was significantly faster (on step-forward time and performance time measures), when compared to the two-step lunge at their pre-specified lunge distance. However, it is not known if similar results could be retrieved for different lunge distances. Further research may explore the following:

i) the effect of the number of lunge steps and players' leg length on maximal lunge distance, total task duration and lunge velocity; and
ii) the effect of the number of lunge steps, players' leg length and pre-specified lunge distance on total task duration (see Table 2) and lunge velocity.

Lin et al. [18], Lam et al. [19] and Nadzalan et al. [14] reported on the results of statistical significance difference analysis on lunge distance. According to Lin et al. [18], no significant difference was found for lunge distance among shod players with shoes of different midsole thicknesses. Lam et al. [19], meanwhile, reported no significant variance in the lunge distance among elite and intermediate players. Interestingly, Nadzalan et al. [14] found that lunging with the dominant limb resulted in significantly greater distance, when compared to lunging with non-dominant limb. Their study concluded that more training focusing on the non-dominant foot was needed to avoid performance imbalance and to reduce injury risks [14].

As a result, the findings showed that only three articles [14,18,19] explored significant difference analysis in badminton lunge distance. Further research on lunge distance is required to bridge the existing knowledge gaps.

3.3. Plantar attributes

Several researchers have considered plantar attributes in lunge movements in footwear design to attenuate loading. Studies concerning plantar attributes have given insight into footwear design modifications for better cushioning effects to mitigate injury risks. The plantar surface is commonly classified into four main regions: toes, forefoot, midfoot and rearfoot (heel) [29–31], and is further divided into sub-regions, as displayed in Fig. 3.

Plantar attributes have commonly been analysed from the perspectives of pressure, maximum force and force-time integral, as well as contact area, as elaborated in the following subsections.

3.3.1. Pressure, maximum force and force-time integral

The plantar regions were examined in different lunge directions [29,30] (see Fig. 3). Hong et al. [30] reported greater peak pressure in the heel and total foot regions for left-forward lunges, when compared to other lunge directions; suggesting that the left-forward lunge is the critical lunge manoeuvre. Hu et al. [29] reported greater peak pressure and maximum force at the great toe region for left-forward and right-forward lunges, in comparison to front-forward lunges. The findings suggested that left-forward and right-forward lunges were critical lunge manoeuvres.

The different lunge steps that were employed (the three-step lunge in Hong et al. [30] and the one-step maximum lunge in Hu et al. [29]) may have caused this discrepancy. Future research may want to concentrate on the difference in plantar attributes between one-step and multiple-step lunges.

Mei et al. [31] investigated the relationships between plantar peak pressure, force-time integral and foot region in elite and recreational badminton players when performing right-forward lunge. Their findings suggested that the elite players' foot loading shifted from lateral rearfoot, medial forefoot, and finally the hallux during the stance phase, as displayed by higher plantar attributes in these regions.

Conversely, the recreational players showed higher plantar attributes in the lateral forefoot and other toes during weight acceptance and amortisation stages of the stance phase. This effect may result in foot ligament injuries and calluses to the lateral forefoot [32,33]. Improvement in foot landing techniques among recreational badminton players is, therefore, needed to avoid injuries.

3.3.2. Contact area

The foot contact area offers insights for stability and comfort study, in which larger foot contact area denotes greater gait stability to prevent one from falling [34,35]. At the same time, more uniform plantar pressure distribution improves foot comfort [36]. Nonetheless, only one article [29] has reported on foot contact area attributes for different lunge directions. However, the researchers found no significant

(a) (b)

Legend:

Total foot (TF)	Second and third metatarsal head (2MH)
Medial heel (MH)/ medial rearfoot (MR)	Fourth and fifth metatarsal head (4MH)
Lateral heel (LH)/ lateral rearfoot (LR)	Medial forefoot (MF)
Medial midfoot (MM)	Lateral forefoot (LF)
Lateral midfoot (LM)	Great toes (GT)/ hallux (H)
First metatarsal head (1MH)	Lateral toes (LT)/ other toes (OT)

Fig. 3. Plantar region segregation illustration as mentioned in (a) Hong et al. [30], Hu et al. [29], and (b) Mei et al. [31].

variance in foot contact areas among left-forward, front-forward and right-forward lunges [29]. Contact area did not seem to be an important determinant in badminton lunge study, but more studies on the contact area are needed to support this interpretation.

3.4. Ground reaction force

The ground reaction force is an important kinetics attribute that affects velocity. Hunter et al. [37], for example, investigated the effects of braking, propulsive and vertical ground reaction force impulses on the velocity of sprint athletes. Similarly, the effect of the ground reaction force in badminton lunges was studied for performance analysis. Several articles have analysed the horizontal, transverse and vertical component ground reaction forces in badminton lunges (see Fig. 2). Ratio normalisation of ground reaction forces to body weight has commonly been adopted to remove the effect of body mass covariate. Several badminton lunge articles [18–21,23,25,30] have reported ratio-normalised ground reaction forces. This ratio normalisation approach has been validated by Mullineaux et al. [38].

However, some articles [13,22,39] have reported ground reaction forces without ratio normalisation. Nadzalan et al. [24] reported ground reaction forces both with and without ratio normalisation. As indicated by Newton's Second Law of Motion, force is directly proportional to mass. Therefore, theoretically, researchers should apply ratio normalise ground reaction force to body mass.

In badminton, the ground reaction force was assessed during the stance phase via force plates, from the time a player landed his/her heel to hit the shuttlecock until the time the foot was fully lifted off the force plate (see Table 2). Ground reaction forces are also useful in explaining and comparing players' lunge motions. For instance, Kuntze et al. [13] reported a larger vertical ground reaction force for hop lunges, as compared to kick lunges and step-in lunges during loading. Their article determined that an extensor force was generated by the knee joint in lifting the leg off the ground before the secondary ground contact, resulting in a larger vertical ground reaction force for the hop lunge.

Nadzalan et al. [24], however, reported greater peak and mean vertical ground reaction forces and impact forces in jump-forward lunges as compared to step-forward lunges. This was similar to the observations for the hop lunge in Kuntze et al. [13]. Lin et al. [20], meanwhile, reported a greater first peak vertical ground reaction force for the three-step lunge (with greater velocity), when compared to the two-step lunge.

Hong et al. [30], on the other hand, found greater peak vertical ground reaction forces for the left-forward lunge, as compared to the right-forward, left-backward and right-backward lunges. The overall findings here suggest that the left-forward lunge is the critical manoeuvre for badminton biomechanics analysis.

Greater vertical and horizontal ground reaction forces at the drive-off phase generated higher speed, contributing to shorter recovery duration time, as shown for the hop lunge in Kuntze et al. [13]. Similarly, Fu et al. [25] reported a higher vertical ground reaction force at the drive-off phase for professional players, when compared to amateur players. Their article concluded that professional players were superior to amateur players in having stronger knee extensors [25,27,40].

Interestingly, Lam et al. [21] also compared the kinetics of single movement (SM) and repeated movement (RM) badminton lunges. A smaller maximum loading rate of vertical impact force, but a larger peak horizontal resultant force, was reported for RM, in comparison to SM. Nonetheless, no significant information was obtained as the kinetics attributes were reported only for the general stance phase. More insight could be obtained by assessing the kinetics attributes; particularly the sub-phases of stance, i.e. braking and propulsion phases (see Table 3).

Aside from ground reaction force, the time to peak force seems to be an integral lunge determinant [40]. The time to peak force has been reported in several articles [18,22,24,30]. A significantly longer time to peak force was reported in jump-forward lunges as compared to step-forward lunges in Nadzalan et al. [24]. On the other hand, no significant difference was reported for the time to peak force for different lunge directions in Hong et al. [30]. Regrettably, no further explanation was provided in Nadzalan et al. [24] and Hong et al. [30] regarding these observations.

Studies on ground reaction forces for badminton games have also been extended to footwear design to prevent injuries. Specifically, ground reaction forces during lunge movement have been assessed for impact attenuation study in footwear. Ryue et al. [23] and Lam et al. [19] compared the vertical impact force and loading rate for different heel shapes of shoes (i.e. rounded heel shoes, standard heel shoes and flattened heel shoes). Lin et al. [18] investigated the ground reaction forces during lunge movements for different midsole thicknesses in footwear. The time to peak force was also analysed but no significant difference was noted between varied thicknesses of shoes [18].

Gammelgaard et al. [22] compared the ground reaction force and time to peak force in shoes of different toe wedge heights. Significant differences were observed only for the time to peak force. Nevertheless, Gammelgaard et al. [22] disregarded these significant differences as the results were clinically invalid due to the horizontal and vertical impulses not being statistically significant. Their article showed that toe wedge height modifications did not significantly affect lunge performance [22].

3.5. Joint attributes

Badminton lunge biomechanics relates to lower body extremity and body trunk movements. The body segment motions have usually been observed by capturing systems involving built-in marker suits or cameras with relevant markers attached at the body joints (see Fig. 4). The marker-based motions captured were then processed using software embedded in the capturing system package to record the numeric data [41].

The important lower extremity joints identified in most badminton lunge studies were the hip, the knee and the ankle. Nonetheless, body trunk attributes were also considered in three articles [14,26,27]. Joint attributes are sometimes detailed by motion directions in three planes to investigate players' lunge performances, as well as injury risks mitigation (see Table 4).

Kuntze et al. [13] compared the hip, knee and ankle attributes

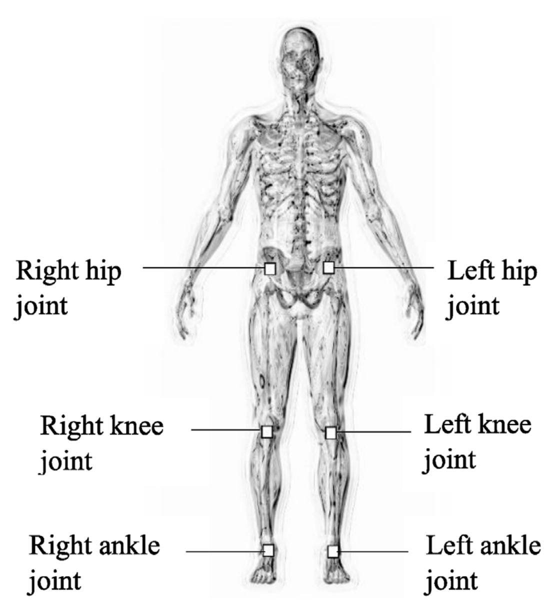

Fig. 4. Joints at body trunk and lower extremity considered in badminton lunge studies.

Table 4
The hip, knee and ankle motion components by plane.

Joint	Motion component	Plane
Hip	Flexion/extension	Sagittal
Knee	Plantar flexion/dorsiflexion[a]	
Ankle[a]	Abduction/adduction	Frontal
	Inversion/eversion[a]	
	Internal/external rotation	Horizontal

[a] The ankle has different terminology for the motion component in the sagittal and frontal plane.

(moment and power) in kick, hop (first and second contacts during the stance phase) and step-in lunges in the sagittal plane. Unlike the kick and step-in lunges, a hop was performed during the weight-acceptance phase for the hop lunge. The non-contact duration during the hop lunge separated the contact phase into two parts (first and second contact phases). Peak ankle moment and power, along with peak knee power of the second contact phase, were significantly greater than in the kick and step-in lunges. Kuntze et al. [13] deduced that the greater the power output in hop lunges, the higher the lunge efficiency.

Conversely, the step-in lunge showed significantly lower peak hip power than the kick lunge and the hop lunge (second contact phase). This indicated that muscular work was reduced during recovery, thereby reducing muscle fatigue for the step-in lunge. On the whole, Kuntze et al. [13] suggested that the hop lunge allowed higher positive power output (second contact phase), while the step-in lunge reduced muscular demand during the recovery phase.

Mei et al. [31] reported on the differences in hip, knee and ankle motions among national-level athletes and recreational college-level players. Smaller ankle eversions and internal rotation movements were observed for recreational players, indicating the poor landing technique of the dominant leg. Greater ankle dorsi-plantar flexion movement was reported for recreational players. Such effects led to higher tendency for calf muscle fatigue and overuse injuries in the ankle and foot [8,9,31,32,42,43]. Meanwhile, greater ankle dorsi-plantar flexion movement also caused fatigue and injury in the calf muscle and the connected Achilles tendon [8,9].

As for knee joint, Mei at al [31]. reported greater peak knee adductions and internal rotation angles for elite athletes. Huang et al. [26] and Lin et al. [27] compared the knee motions of players with and without knee pain (injured and control groups). Smaller knee abduction-adductions and internal-external rotation ranges of motion (ROM) were found for the injured group. The authors reasoned that the injured group adopted a conservative strategy (reduced knee ROM in frontal and horizontal planes) to avoid stressing their injured knees. However, the reduced knee ROM adversely affected lunge performances for the injured group [26,27].

The collective findings for elite athletes, as reported in Mei et al. [31], and the control groups in Huang et al. [26] and Lin et al. [27], agreed that greater knee frontal and horizontal plane ROM indicated good lunge performances.

Mei et al. [31] also suggested that smaller hip and knee flexion had been ideal, as observed in the elite athletes' lunging capabilities. Lunging with the knee not extended beyond the toes and with minimised hip flexion enabled players to return to the base position (the recovery phase) at a quicker pace [31]. Huang et al. [26], meanwhile, observed greater knee flexions in their knee-injured group to cushion the injured joint during landing impact. The suggestion that smaller hip and knee flexions as good lunge performance indicators is in line with that reported by Huang et al. [26].

Researchers have not focused on the lower body extremities alone. Trunk attributes and upper extremities' movements have been considered in badminton lunge performance analysis. For example, the arm-forward position contributes to the forward movement of COM, thus enhancing forward lunge task performance [26,27,44]. The arm-forward position is made up of a greater hip-shoulder separation angle, shoulder-arm separation angle, and, indirectly, trunk tilt angle.

The hip-shoulder separation angle, the shoulder-arm separation angle and the trunk tilt angle were collectively investigated by Huang et al. [26] and Lin et al. [27], who compared the results between injured and control groups. They found cases of greater hip-shoulder separation angles for the control group in both forward and backward lunges during the lunge and recovery phases. This suggested better control in core muscles and improved balance stability.

Similarly, greater shoulder-arm separation angles were found in the control group for forward lunges during the lunge and recovery phases. In addition, trunk tilt angles were significantly smaller in the injured group for backward lunge.

The results from these studies showed that the injured group applied trunk-stiffening movements due to poor neuromuscular control of trunk muscles. The lack of trunk tilting in the sagittal plane was compensated for with greater knee flexion in the sagittal plane.

Nadzalan et al. [14] compared knee, hip, ankle and trunk angles in step-forward and jump-forward lunges. However, no significant difference was observed based on the outcomes. Joint kinetics was also investigated in Lin et al. [20], who reported greater hip adduction torques in three-step lunges, when compared to two-step lunges. Unfortunately, no detailed explanation or further information has been made available.

Fu et al. [25] compared joint loading among national-level professional players and college-level amateur players during the segregated stance phase, as shown in Table 3. The professional players showed significantly greater knee abduction moments in initial impact peaks and greater knee extension moments in secondary impact peaks. Overloading on knee joints may lead to internal cruciate ligament, collateral ligament and meniscus injury [25,45–47].

On the other hand, amateur players showed greater inversion moments (smaller eversion moments) than professional players, particularly at the weight-acceptance phase (see Table 3). Fu et al. [25] determined that greater inversion moments may result in ankle inversion sprain injuries [48,49]. Significant differences observed in ankle internal-external rotation moments indicated the adoption of different ankle stability mechanisms.

The authors' findings showed that amateur players required correct techniques of coaching, as proven by their attributes' deviation from that of professional players. Professionals, meanwhile, had to be cautious of the higher loading impact on their knees because of the higher potential risks of ligament injuries.

Unlike other articles which studied joint angles and moments, Lam et al. [21] explored the joint muscle force between SM and RM in five consecutive lunges. Smaller peak knee anterior-posterior forces and peak knee sagittal moments were reported for RM lunges. This proved the influence of RM lunges on players' joint attributes during lunge performance.

Joint attribute analysis was also extended to players' footwear in relation to their lunge performances. Lin et al. [18] investigated ankle inversions among shod players with different footwear midsole thicknesses. Gammelgaard et al. [22] compared the hip, knee and ankle joint angles and moments between shod players with different toe wedge heights.

Ryue et al. [23] and Lam et al. [19] compared knee joint moments between shod players with different shoe heel shapes (rounded heel shoes, standard heel shoes and flattened heel shoes), but reported no significant difference in knee moments during lunges. Park et al. [15] compared peak and ROM of the ankle (in the sagittal, frontal and horizontal planes) in shoes of different bending stiffness. However, they found no significant difference in ankle attributes during badminton lunges [15].

Wei et al. [50,51] looked into metatarsophalangeal joint angle, angular velocity and joint stiffness among players shod with their custom-made shoes prototype and Yonex shoes, and unshod players. A major highlight of the research was that joint attributes were important determinants in badminton lunge performance. Joint attributes gave information on different lunge techniques; for example, on the kick and step-in lunges. Future research could extend the experimental protocol limitations to include all relevant joints that contribute to significant performance in lunge motions.

In most studies [25–27,31], statistical comparisons were only performed between two subject groups. Statistical comparison analysis could be extended to more than two study groups to improve outcome reliability.

3.6. Dynamic balance attributes

Dynamic balance attributes have been considered in badminton to measure the stability of players' motions around the court. Only two articles [26,27] that specifically reported on the dynamic balance attributes concerning badminton lunge motions. Huang et al. [26] and Lin et al. [27] investigated dynamic balance attributes among badminton players with and without knee injuries in forehand and backhand lunges, respectively.

The attributes considered were peak centre of mass (COM) velocity and relative displacement between COM and centre of pressure (COP) during the hitting and recovery phases of the lunge (see Table 3). COM velocity reflects the players' weight-shifting ability, i.e. the ability to shift their COM swiftly, whereas COM-COP displacement gives insight into the players' balancing strategy.

3.6.1. Peak COM velocity

The peak COM velocity is commonly quantified in gait analysis to gain information on balancing capabilities [52–54]. For example, an increase in medial-lateral COM motion during obstacle-crossing in gait analysis indicated poor balancing (greater risk of falling) [52]. In badminton lunge analysis, Huang et al. [26] found no significant difference in anterior-posterior peak COM in forehand forward lunges (FFL) among the control group and the injured group during the hitting and recovery phases. The article inferred that the FFL was commonly used in badminton and had lower difficulty, as compared to the forehand backward lunge (FBL).

The injured group was able to perform the FFL, including the control group. Additionally, the control group showed significantly higher medial-lateral peak COM velocities for both FFL and FBL. The authors concluded that the control group had better weight-shifting abilities in relocating their COM when necessary in their balancing strategy.

However, the upward-downward peak COM velocities of the control group were only significantly higher in the hitting phase and not in the recovery phase for FFL and FBL [26]. Similar observations were reported for backhand forward lunge (BFL) in Lin et al. [27]. Upward-downward COM velocity was important because the experimental protocols were developed such that the shuttlecock was hit at the height level of the players' anterior superior iliac spine (ASIS) [26,27].

Therefore, players were required to lower their COM to the height of the ASIS in order to hit the shuttlecock. The control group showed higher upward-downward peak COM velocities, thus proving greater control over their knee joints to perform lunges efficiently.

3.6.2. Relative COM-COP displacement

Besides COM motion, relative COM-COP displacement was commonly considered in evaluating dynamic stability in gait analysis [53,55–57]. In badminton lunge studies, Huang et al. [26] and Lin et al. [27] reported contradictory results on COM-COP displacements for players with knee injuries. It remains unknown if knee injury would result in greater or reduced COM-COP displacement.

Huang et al. [26] and Lin et al. [27] presented different explanations to support their respective results. Lin et al. [27] deduced that the injured group reduced their relative COM-COP displacements to minimise loading moments on supporting joints. On the contrary, Huang et al. [26] reported greater relative COM-COP displacement for the injured group, suggesting that the injured players did not shift their COM much (i.e. lower weight-shifting ability).

The injured group did not shift their COM to the injured knee to minimise loading stress over the injured knee. However, this resulted in greater loading moment on the supporting limb due to greater COM-COP displacement [26]. This interpretation [26] of the injured group's greater COM-COP displacement was supported by Hahn and Chou [53], who compared COM-COP displacement between healthy group of elderly adults and young adults in gait analysis (obstacle-crossing). Their study found that the healthy elderly adults reduced their COM-COP displacement in order to minimise muscular effort (i.e. a conservative strategy) to counterbalance loading moments [53]. The injured group in Huang's et al. [26] study failed to apply this strategy (reducing COM-COP displacement) due to knee injuries.

The limitation in both the studies by Huang et al. [26] and Lin et al. [27] was that the specific type of knee injury was not diagnosed. Different types of knee injuries could have prompted the players to apply different movement strategies. This limitation resulted in the contradictory results reported for relative COM-COP displacements.

Thus, more studies on dynamic balance attributes, especially COP-COM displacement amidst badminton players with knee injuries, are needed to evaluate the contradictory findings reported by Huang et al. [26] and Lin et al. [27]. Lunging with an injured knee will result in different posture adaptations (e.g., different COM velocities and COM-COP displacement), which can adversely affect the players' lunge performances [26,27]. Complete understanding of the impact of historical knee injuries on players' balancing capabilities during lunge performance is essential to optimise training programme effectiveness, while at the same time, preventing injuries.

3.7. Muscle attributes

3.7.1. Electromyography data

One of the major focus areas in badminton sports and health science disciplines is neuromuscular control (muscle activation). Huang et al. [26] and Lin et al. [27] investigated the differences in muscle activity among badminton players with and without knee injuries during forehand and backhand lunges, respectively. Electromyography data for left paraspinal (LPA), right paraspinal (RPA), vastus lateralis (VL), vastus medialis (VM), medial gastrocnemius (MG), left external abdominal oblique (LEO), right external abdominal oblique (REO) and hamstring (HAM) muscles at pre- and post-impact stages were collected by Huang et al. [26]. However, only LPA, VL, VM and MG muscles data during lunge phases were studied in Lin et al. [27].

The studies on electromyography data revealed several reasons for the badminton players to suffer from knee injuries, including:

i) greater knee flexion required in advance to cushion the knee joint during impact (greater pre-impact hamstring muscle activity);
ii) failure to apply feedforward activation to minimise knee injury risk (lower pre-impact paraspinal muscle activity) [26];
iii) inefficient quadriceps contraction to support impact force (lower activity in VL and VM muscles);
iv) lower weight-bearing ability (lower activity in MG muscle); and
v) a trunk stiffening strategy application based on greater activation on the non-dominant side paraspinal muscle to maintain balance by adopting an asymmetric posture [27]. The asymmetric posture adopted was to counterbalance the racket loading on the dominant hand [27,46,58].

It is therefore understood that knee injuries have adverse effects on neuromuscular control in badminton lunge performance. Special training programmes could be designed to improve neuromuscular control, as well as muscle strength of muscles and knee extensors [26,27].

Nadzalan et al. [59] studied the differences in muscle activities in dominant and non-dominant limbs in step-forward lunges and jump-forward lunges. Electromyography data on VL, VM, rectus femoris (RF), biceps femoris (BF), gluteus maximus (GM), medial gastrocnemius (MG) and lateral gastrocnemius (LG) muscles were evaluated. Jump-forward lunges had greater muscle activations, as compared to step-forward lunges. Muscle activation on the dominant side was greater than the non-dominant side. These findings suggested that a jump-forward lunge training routine was preferable for muscle and strength development.

3.7.2. Muscle force and work done

Lees and Hurley [39] studied the muscle forces of gastrocnemius, rectus femoris, patellar tendon, hamstring and gluteal muscle groups. The study highlighted peak force for the hamstring and gluteal muscle groups at the loading phase, causing rapid muscle eccentric action. This explained the delayed onset muscle soreness (DOMS) experienced by badminton players not accustomed to lunge movements [39]. DOMS often occurred after intensive eccentric muscle exercise [60–62].

On the other hand, Lund et al. [63] studied the elastic energy return (work done) by passive, tendon and muscle elements of the gastrocnemius and soleus muscles during right-forward badminton lunges for different distributions of footwear insole hardness. Their findings were biased towards footwear ergonomics; in particular, the effects of insole hardness distribution on work done were not determined. The elastic energy storage that occurred was mainly in the soleus muscle-tendon units (the soleus showed greater work done compared to the gastrocnemius for all footwear types).

4. Role of computers in badminton lunge analysis

The evolution of computer technology and the advent of sensors have paved the way for more efficient badminton lunge data collection and analysis. Specifically, the advancement of computerised motion recognition and analysis in sports science via input acquisition sensors and computer hardware have contributed much to this domain [64]. Badminton motion recognition analysis involves computational analysis of video sequences produced by cameras or sensors that are converted digitally into sequential images or frames for tracking (also known as a video digitisation system).

Human motion capture (mocap) can be performed either by marker-based or markerless methods. Although the marker-based method produces more accurate measurements, marker attachment impedes the naturalness of players' movements [65]. Nevertheless, marker-based motion capture was prevalent in the 21 badminton lunge analysis articles reviewed. Joint kinematics was commonly captured using infrared motion analysis systems consisting of surrounding cameras and reflective markers [13,15,18–22,25–27].

To focus on the coordination of foot loading (ground reaction force), as discussed in Section 3.4, force plates such as Kistler force plates [13,20,25–27] and Advanced Mechanical Technology (AMTI) force plates [18,19,21,22] were used for ground reaction force measurements. A digital data acquisition system (DAQ) converted charges from the force plates' piezoelectric sensors to digital signals. The digital signals were then read by computers with the aid of embedded software to output ground reaction force time-series data [66].

The recorded time-series data were analysed via low-pass filtering, using second-order [22] and fourth-order [15,19,21] Butterworth filters. Limb segment model reconstruction and joint kinetics computation were performed using the inverse dynamic approach with the aid of computer software packages such as CODAmotion [13], Vicon Clinical Manager Software [19,21], and Visual3D [19–21].

The pre-processed lunge motion data were quantified statistically using computer-aided statistical package tools such as SPSS repeated-measures ANOVA [13,15,19,22], multivariate analysis of variance (MANOVA) [26], paired samples [13,21,22,67] and independent samples *t*-test [25,27].

Past studies have looked into the statistically significant differences in lunge attributes (see Fig. 2), categorised by lunge directions [29,30], level of players [25,31], and health of players [26,27], by evaluating the statistical significance (p-values) and effect sizes [68].

The major findings were:

i) greater foot loading was observed in the left-forward and right-forward lunges, indicating two critical lunge directions for research analysis [29,30];
ii) amateur players needed to improve their foot landing techniques to avoid injury [25,31]; and
iii) players with injured knees adopted a more conservative posture to avoid knee pain recurrence, but this approach hindered their game performance [26,27].

5. Conclusion

Comprehending the important attributes that are aligned with lunge motions enables correct badminton game postures in order to improve performance and minimise injury risks. Hence, it is crucial to study the effects of the main attributes on lunge skills, as improvement of the quantitative attributes are reflected in lunge skills' improvement.

Existing studies have concentrated on the popular areas of ground reaction forces, as well as plantar and joint attributes. This paper has bridged a knowledge gap by highlighting lunge attributes for future research, and by encouraging more emphasis on less-explored attributes, such as time, lunge distance, dynamic balance and muscle attributes.

In reality, time attributes are important indicators of lunge performance as they gauge players' ability to lunge quickly to hit the shuttlecock. Furthermore, lunge distance ought to be more comprehensively considered in future studies as the lunge distances in actual matches may be different from the predefined lunge distances in experimental studies (i.e. during training).

Dynamic balance attributes can also provide insights into players' lunge postures, while analysis of dynamic balance attributes, such as peak COM and relative COM-COP displacement, has been inadequate. As for muscle attributes, electromyography data, in particular, have given information concerning the activation of specific muscles during lunge tasks. This information can serve as supplementary material to identify muscular demands on specific joints.

Overall, researchers should be made aware that badminton lunge analysis involves complex biomechanics that is subject to various external and historical determinants, all of which may be significant to better understand lunge skills improvement and injury risks mitigation.

Conflicts of interest

The authors declare that there is no conflict of interest.

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