

Article

Changes in the Kinematic and Kinetic Characteristics of Lunge Footwork during the Fatiguing Process

Yanyan Du ^{1,2} and Yubo Fan ^{1,3,*}

¹ Key Laboratory for Biomechanics and Mechanobiology of Ministry of Education, Beijing Advanced Innovation Centre for Biomedical Engineering, School of Biological Science and Medical Engineering, Beihang University, Beijing 100083, China; duyanyan@cupes.edu.cn

² Beijing Key Laboratory of Sports Function Assessment and Technical Analysis, Capital University of Physical Education and Sports, Beijing 100191, China

³ School of Medical Science and Engineering, Beihang University, Beijing 100083, China

* Correspondence: yubofan@buaa.edu.cn; Tel.: +86-10-82339428

Received: 29 September 2020; Accepted: 2 December 2020; Published: 4 December 2020



Featured Application: 1. The kinematic and kinetic characteristics of the lunge maneuver were gradually impaired in the fatiguing process. 2. Period IV (pre-drive-off) of the stance phase showed the most significant fatigue response. 3. Improving the strength of the knee extensor is important for the lunge maneuver, particularly in period IV. 4. It is important to improve the strength of hip extensors for the lunge maneuver. 5. The analysis of waveform data is more useful for the assessment of weak areas of the body and periods of motion.

Abstract: Fatigue is a major injury risk factor. The aim of this study was to investigate the effects of fatigue on lunging during the fatiguing process. The lower extremity joint kinematics and kinetics of fifteen male collegiate badminton players were simultaneously recorded by optical motion-capture and force plate systems during lunging. In addition to statistical analyses of discrete variables, one-dimensional statistical parametric mapping (SPM (1D)) was used to analyze the waveform data. The hypotheses were that the biomechanics of lunging maneuvers would change during the fatiguing process, and the fatigue effects would differ in different periods (I–V) of the stance phase and in different joints. Results showed that the initial contact angles, peak angles, moments, power, and time needed to reach the peak angles at the hip, knee, and ankle in the sagittal plane all decreased post-fatigue. A continuous decreasing tendency was reflected in the moments and power of hip and, in particular, knee joints (mostly $p < 0.001$). Period IV showed a significant fatigue response. In conclusion, both discrete and waveform data illustrated the effects of fatigue, however, the results of SPM (1D) analysis showed both the key period and body segments affected by the fatigue response.

Keywords: badminton; knee joint; injury; one-dimensional statistical parametric mapping

1. Introduction

Badminton, one of the most popular sports globally [1–4], is the fastest non-contact racket sport, and requires a combination of strength, speed, and stamina. While playing this sport, players must repetitively lunge, jump, and quickly change direction from a wide variety of positions. A previous epidemiology study conducted in Ireland reported that badminton was the sport with the most injuries [5]. Lower extremity injuries accounted for 43 to 86% of all injuries regardless of the nationality [6], and overuse is considered the major reason [7,8]. Ankles and knees are the most injured sites [1,7,9], particularly the knee joint [7,8]. Patellar tendinopathy [7] is the most common type of knee injury. As a specific and often-used example of footwork [10,11], the repetitive lunge is a likely cause of patellar tendinopathy, particularly for teenager players [3,12].

Moreover, epidemiology studies have also shown that a higher badminton injury rate was found at the end of a match or training [13], and higher rates have been found during training [7,14]. This could be explained by a higher intensity of training routine [7], which may induce fatigue. Because fatigue reduces the capacity of muscles to generate force, it may be an important factor causing injury. In badminton, increased ankle sprain injuries were found to occur at the end of a training or match session due to the accumulation of fatigue [6]. Due to fatigue caused by repeating the forward lunge, the activity of the vastus lateralis, vastus medialis, and biceps femoris showed a significant change [15], and knee injury risk was increased [16].

A number of studies [10,17–21] have investigated the biomechanical characteristics of the lunge, particularly its stance phase, which is defined as the period of time from initial contact to final lift-off from the ground by the dominant limb [10]. Ankle sprain [6] and patellar tendinopathy [14] may occur during the stance phase. However, the relationship between the repetitive lunge and injury is still not clear. A previous study examined the lunge under the condition of exhaustion to investigate the fatigue effect on the knee [16]. A limitation of this study is that the changes of lunge motion during the fatiguing process were ignored. Injury usually occurs at a certain time, instantaneously, and the factors inducing injury are prolonged. However, we are unaware of any studies that have investigated the biomechanical changes during the fatiguing process in badminton. Therefore, there is a lack of objective data on lower joint kinematics and kinetics of the lunge during the fatiguing process, which may provide essential insight into the understanding of the mechanism of injury.

Additionally, discrete data (related, for example, to the peak angle) has traditionally been used for statistical analysis to confirm the differences outlined above. However, it is worth noting that all kinematic and kinetic variables are continuous variables with time. Furthermore, as mentioned above, injury occurs partly due to the accumulation of changes. Thus, continuous data analysis may provide other useful information. In recent years, one-dimensional statistical parametric mapping (SPM (1D)) has been accepted as an effective method to analyze waveform data [22]. Kinematic waveform data of hip, knee, and ankle joints in three planes, measured in players with different levels, have been analyzed by SPM (1D) [18,19]. However, to the best of the authors' knowledge, no research has investigated the fatigue response by analyzing the biomechanics waveform data of the lunge.

Consequently, the purpose of this study was to investigate the changes of lunge biomechanical characteristics during the fatiguing process, from normal to fatigued states. To achieve this objective, a repetitive forehand forward lunge to exhaustion was proposed as the fatigue protocol. The fatiguing process was divided into sub-stages. In addition to the discrete data (ground reaction force (GRF), lower extremity joint angles, range of motion (RoM), moments, and power), waveform data (GRF and lower extremity joint angles, moments, and power) were also analyzed during different fatiguing stages. The hypotheses are (i) both discrete and waveform data of lunge biomechanical characteristics change significantly during the fatiguing process, especially post-fatigue; (ii) effects of fatigue vary with different periods of the stance phase; and (iii) the lower limb joints have different fatigue responses.

2. Materials and Methods

2.1. Participants

Fifteen male collegiate badminton players (age: 21.1 ± 2.2 years; height: 1.81 ± 0.04 m; weight: 72.5 ± 8.4 kg; years of badminton training: 8.9 ± 3.5 years) were recruited for the study. All participants were free from any injuries within the previous 3 months and did not take part in any high-intensity training or competitions during the two days prior to the experiment. All participants were informed of the procedures and requirements of the test, and written informed consent was obtained from each participant. In addition, a questionnaire about anthropometrics, health status, injury history, and physical activity level was completed. To minimize the potential effect of footwear, participants wore badminton shoes and socks of the same brand and series. The study was approved by the ethics committee of Beihang University (No. BM201900077).

2.2. Experimental Protocol

The test was conducted on a simulated badminton court of the biomechanics laboratory. Prior to the test, participants performed a familiarization of the forehand forward lunge and the study protocol, which included 10 min warm-up; tests of heart rate (HR), blood lactate (BL), and Borg 6–20 rating of perceived exertion (RPE); and a fatigue protocol. Considering the dependency of fatigue on the task being undertaken [23,24] and the aim of this study, repeating the forehand forward lunge until participants reached the state of exhaustion was proposed as the fatigue protocol [16]. More specifically, a forehand forward lunge cycle was defined as lunging from the starting position using the dominate limb with a sliding step, landing on the force plate positioned at the right front, hitting one shuttlecock, and then moving backward to the starting position. The degree of fatigue was estimated by values of HR [15], BL, and RPE [25], which were measured before (pre) and immediately after (post) the fatigue protocol.

A system of 9 optoelectronic cameras (Oqus 300+ Series, Qualisys AB®, Gothenburg, Sweden) and a Kistler mobile multi-component force plate (Type 9286A, Kistler, Kistler Instrument AG, Winterthur, Switzerland), integrated into the walkway, were used to record the marker position and ground reaction forces, and synchronized at 200 and 1000 Hz, respectively. According to the color atlas of skeletal (CAST) landmark definitions of the lower leg [26], twenty-eight reflective markers (diameter: 18 mm) were attached to the lower extremity for dynamic motion capture. The locations included anterior superior iliac spines, posterior superior iliac spines, thigh (markers cluster), shank (markers cluster), calcaneus, hallux, and 2nd and 5th metatarsal head of the left and right lower extremity. The markers on calcaneus, hallux, and 2nd and 5th metatarsal head were placed on the corresponding anatomical location of the badminton shoes.

2.3. Data Analysis

The kinematic and force data were obtained by the optical motion-capture system and then exported and saved as c3d files. Then, the hip, knee, and ankle joint angles, moments, power, and ground reaction force (GRF) were calculated using visual 3D software (V5, C-Motion, Bethesda, MD, USA). The raw kinematic data were filtered with a low-pass (Butterworth) filter with frequency of 20 Hz [10]. The threshold of the vertical ground reaction force (vGRF) data was set as 10 N.

The stance phase, from initial contact (heel strike) to final lift-off from the force-plate by the dominant limb, was determined by the vGRF value. During this phase, there were three vGRF peaks, namely, the initial impact peak (PF1) for heel strike transient, the secondary impact peak (PF2) for impact loading, and the third impact peak (PF3) for drive-off. Based on the classification of previous studies [10,20,21], five periods can be clearly identified in the stance phase: (I) initial contact (from heel strike to PF1); (II) impact loading (from PF1 to PF2); (III) weight acceptance (from PF2 to peak knee joint flexion angle (PAK)); (IV) pre drive-off (from PAK to PF3); and (V) drive-off (from PF3 to lift-off from ground). In addition, the fatiguing process was divided into four stages according to the slope of the HR–time curve. Six continuous lunging motions were assessed at the end of each stage, and the kinematic and kinetic data of three lunge motions were then averaged and normalized for further statistical analysis.

During the stance phase, the motion of lower extremity joints, particularly the knee, occurs primarily in the sagittal plane. This contributes to the major knee joint biomechanical characteristics in badminton research [10,21]. Based on the previous literature linked to the lunge in badminton [10,17–21,27], we analyzed the impact peak; duration of five sub-stance phases; hip, knee, and ankle joint initial contact angles; durations to peak angle; ranges of motion (RoM); peak angles; moments; and power in the sagittal plane.

2.4. Statistical Analysis

All variables of the fatiguing process were calculated during four sub-stages. The kinetic data were normalized by body weight. All discrete variables were reported as mean ± standard deviation (SD), and examined for normality using a Shapiro–Wilk test prior to statistical analysis. One-way repeated measures ANOVA was used for the analysis of the influence of fatigue on the related parameters and discrete biomechanical data. Paired *t*-tests were performed to identify the differences. All statistical procedures were performed with SPSS 25 (IBM SPSS Statistics for Window, IBM Corp., NY, USA). Additionally, the waveform data of joint angles, moments, and power in the sagittal plane were analyzed (paired *t*-test) and plotted using one-dimensional statistical parametric mapping (SPM (1D) (<https://spm1d.org/>)) in MATLAB (R2014b, Mathworks, Inc., Natick, MA, USA). In addition, prior to statistical analysis, normality tests were performed for the waveform data with SPM (1D). The statistical significance level was set at 0.05.

3. Results

3.1. Fatigue Protocol

After the fatigue protocol, the mean values of HR, BL, and RPE were greater than 185 beats/min, 14 mmol/L, and a score of 18, respectively. Results of repeated measurement indicated that HR, BL, and RPE were all affected by the fatigue protocol (partial η^2 : 0.99, 0.876, and 0.994 respectively), and the *p* values were all less than 0.001 (Table 1).

Figure 1 illustrates the HR–time curve (mean) of four participants throughout the fatigue protocol. To divide the fatigue protocol into stages, time was normalized, the slope of the HR–time curve was calculated, and four stages were distinguished, namely, P1 (0–10% duration of fatiguing process (D)), P2 (10–30%D), P3 (30–60%D) and P4 (60–100%D).

Table 1. Values of heart rate (HR), blood lactate acid (BL), and rating of perceived exertion (RPE) pre- and post-fatigue protocol (mean ± SD).

	Mean ± SD		η_p^2	95% CI of the Difference		<i>t</i>	<i>p</i>
	Pre	Post		Lower	Upper		
HR (beats/min)	78.2 ± 9.4	185.8 ± 9.1	0.99	−115.013	−100.32	−32.256	<0.001
BL (mmol/L)	3 ± 2.4	14.3 ± 3.1	0.876	−14.241	−8.543	−8.801	<0.001
RPE	6 ± 0	18.4 ± 1	0.994	−13.05	−11.784	−43.176	<0.001

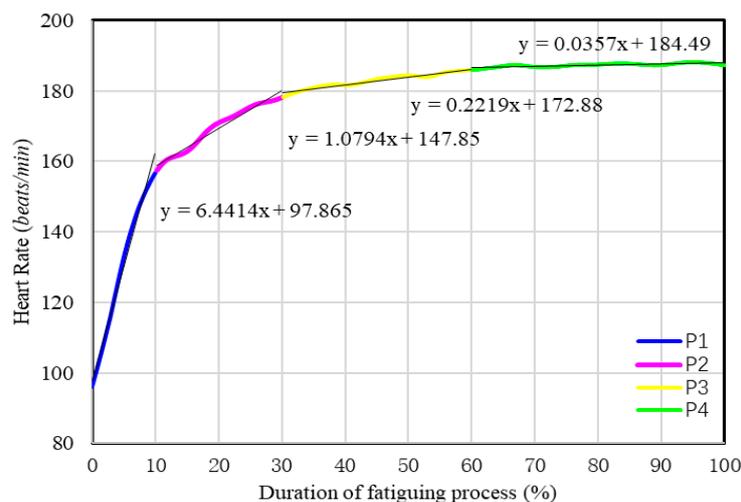


Figure 1. Heart rate (HR) of four participants during the fatiguing process (mean). According to the slope of the HR–time curve, the overall duration of the fatiguing process was divided into four stages, that is, P1, P2, P3, and P4. Duration of fatiguing process (%) vs. heart rate (beats/min).

3.2. Kinematics of Lower Extremity Joints

In the sagittal plane, Table 2 shows that the hip, knee, and ankle initial contact angle (CAH, CAK, CAA, respectively), peak angle (PAH, PAK, PAA, respectively), time to peak angle, and range of motion (RoM) all decreased during the process of the fatigue protocol (from P1 to P4).

Table 2. Kinematics variables in the four stages of fatiguing process (P1–P4) from pre- to post-fatigue protocol in the sagittal plane (mean \pm SD).

	P1	P2	P3	P4	<i>p</i>
Joint angle at initial contact (°)					
CAH	46.08 \pm 12.7	46.12 \pm 10.32	42.2 \pm 11.77	42.17 \pm 11.77	<i>c, d*, e*</i>
CAK	13.11 \pm 7.43	9.65 \pm 7.55	7.82 \pm 6.78	7.87 \pm 6.09	<i>a, b, c*</i>
CAA	10.35 \pm 8.05	6.81 \pm 8.25	8 \pm 8.47	6.42 \pm 9.11	
Peak joint angle (°)					
PAH	74.08 \pm 11.94	73.3 \pm 9.93	67.34 \pm 11.74	67.84 \pm 12.78	
PAK	69.46 \pm 8.77	65.43 \pm 9.44	64.17 \pm 10.26	62.46 \pm 8.84	<i>a*, b, c*</i>
PAA	−20.84 \pm 5.7	−18.74 \pm 5.2	−18.4 \pm 4.9	−18.19 \pm 6.55	
Time to peak joint angle (%)					
PAH	41.63 \pm 6.59	42.13 \pm 8.79	38.88 \pm 7.55	36.75 \pm 6.94	
PAK	45.88 \pm 6.51	38.63 \pm 9.12	37.25 \pm 10.44	33.63 \pm 9.43	<i>c*, f</i>
PAA	14.13 \pm 2.95	12.75 \pm 2.82	12.38 \pm 3.42	11.25 \pm 2.71	<i>a, b, c</i>
Range of Motion (°)					
Hip joint	44.57 \pm 10.44	39.16 \pm 5.09	34.54 \pm 6.85	38.67 \pm 10.8	
Knee joint	59.32 \pm 7.31	56.63 \pm 6.84	56.74 \pm 7.95	55.07 \pm 6.28	<i>a, c</i>
Ankle joint	34.11 \pm 8.09	29.82 \pm 9.46	34.92 \pm 9.68	31.98 \pm 8.23	

Notes: CAH, CAK, and CAA: initial contact angle of hip, knee, and ankle joint, respectively; PAH, PAK, and PAA: peak joint angle of hip, knee, and ankle joint, respectively. P1–P4: the 1st, 2nd, 3rd, and 4th stages of the fatiguing process, respectively. *a, a**: significant differences between P1 and P2 at 0.05 and 0.01 levels, respectively; *b*: significant differences between P1 and P3 at 0.05 level; *c*: significant differences between P1 and P4 at 0.05 level; *d**: significant differences between P2 and P3 at 0.01 level; *e**: significant differences between P2 and P4 at 0.01 level; *f*: significant differences between P3 and P4 at 0.05 level.

At initial contact, a significant decrease was found for hip flexion (P1 vs. P4, $p = 0.044$; P2 vs. P3, $p = 0.009$; P2 vs. P4, $p = 0.003$) and knee flexion (P1 vs. P2, $p = 0.028$; P1 vs. P3, $p = 0.037$; P1 vs. P4, $p = 0.004$). Hip, knee, and ankle joints were all flexed (plantar-flexed) to the peak joint angle in less time. There were statistically significant differences in the time to peak value for the knee joint (P1 vs. P4, $p = 0.009$; P3 vs. P4, $p = 0.012$) and the ankle joint (P1 vs. P2, $p = 0.036$; P1 vs. P3, $p = 0.021$; P1 vs. P4, $p = 0.001$). The significance values (p) of the knee joint RoM were 0.013 (P1 vs. P2) and 0.048 (P1 vs. P4).

3.3. Five Sub-Phases of the Stance Phase

Table 3 shows that significant differences existed in the duration of the sub-stance phases II, III, IV, and V during the fatiguing process: durations were shorter for II (P1 vs. P3: $p = 0.012$), III (P1 vs. P4: $p = 0.041$; P3 vs. P4: $p = 0.005$), and V (P1 vs. P3: $p = 0.021$; P1 vs. P4: $p = 0.005$), and longer for IV (P1 vs. P2: $p = 0.022$; P1 vs. P3: $p = 0.024$; P1 vs. P4: $p = 0.002$; P2 vs. P4: $p = 0.002$; P3 vs. P4: $p = 0.036$).

3.4. Kinetics of Lower Extremity Joints

For the mean moments and power at the hip, knee, and ankle joints in the sagittal plane. Significant differences were found for moments at the hip (the 1st peak, P1 vs. P4: $p = 0.03$; the 2nd peak, P1 vs. P4: $p = 0.01$) and the knee (the 1st peak, P1 vs. P4: $p < 0.001$; the 2nd peak, P1 vs. P4: $p = 0.01$); power generation at the hip (P1 vs. P3: $p = 0.025$; P1 vs. P4: $p = 0.014$) and knee (P1 vs. P2, P1 vs. P3, P1 vs. P4: $p < 0.001$); and power consumption at the knee (P1 vs. P2: $p = 0.029$; P1 vs. P3: $p = 0.009$ and P1 vs. P4: $p < 0.001$) (details in Figure 4a).

3.5. SPM (1D) of Kinematics of Lower Extremity Joints

For the four stages of the fatiguing process (P1–P4), Figure 2a illustrates the joint angle–time curves in the sagittal plane (mean \pm SD). SPM (1D) analysis results with significant differences are illustrated in Figure 2b. At the hip, significant differences exist in the initial contact (I), impact loading

(II), weight acceptance (III), and pre-drive-off (IV) phases (P2 vs. P3 (I and II: $p = 0.01$; III and IV: $p < 0.001$); P2 vs. P4 (I–IV: $p < 0.001$)). At the knee, significant differences were found mainly in the weight acceptance and pre-drive-off phases (P1 vs. P2 and P1 vs. P4: $p < 0.001$).

Table 3. Duration of five sub-phases (%) (mean \pm SD).

	P1	P2	P3	P4	<i>p</i>
Duration of Five Sub-Phases (%)					
I (0-PF1)	3.88 \pm 0.64	4 \pm 0.93	4 \pm 0.76	3.75 \pm 0.71	
II (PF1-PF2)	11.13 \pm 2.75	8.63 \pm 4.44	8 \pm 3.55	8.88 \pm 3.31	<i>b</i>
III (PF2-PAK)	30.88 \pm 6.03	26 \pm 7.11	25.25 \pm 9.25	21 \pm 9.3	<i>c, f*</i>
IV (PAK-PF3)	27.25 \pm 10.69	36.5 \pm 14.32	39.25 \pm 17.17	43.38 \pm 15.24	<i>a, b, c*, e*, f</i>
V (PF3-FO)	26.88 \pm 5.57	24.88 \pm 7.24	23.5 \pm 7.23	23 \pm 6.68	<i>b, c*</i>

Notes: PF1: initial impact peak (the 1st peak vertical ground reaction force, vGRF); PF2: secondary impact peak (the 2nd peak vGRF); PF3: third impact peak (the 3rd peak vGRF); PAK: peak knee joint flexion angle. FO: foot off. The stance phase was divided into five sub-phases (I–V) according to impact peak and PAK. P1–P4: the 1st, 2nd, 3rd, and 4th stages of the fatiguing process, respectively. *a, a**: significant differences between P1 and P2 at 0.05 and 0.01 levels, respectively; *b*: significant differences between P1 and P3 at 0.05 level; *c, c**: significant differences between P1 and P4 at 0.05 and 0.01 levels, respectively; *e**: significant differences between P2 and P4 at 0.01 level; *f, f**: significant differences between P3 and P4 at 0.05 and 0.01 levels, respectively.

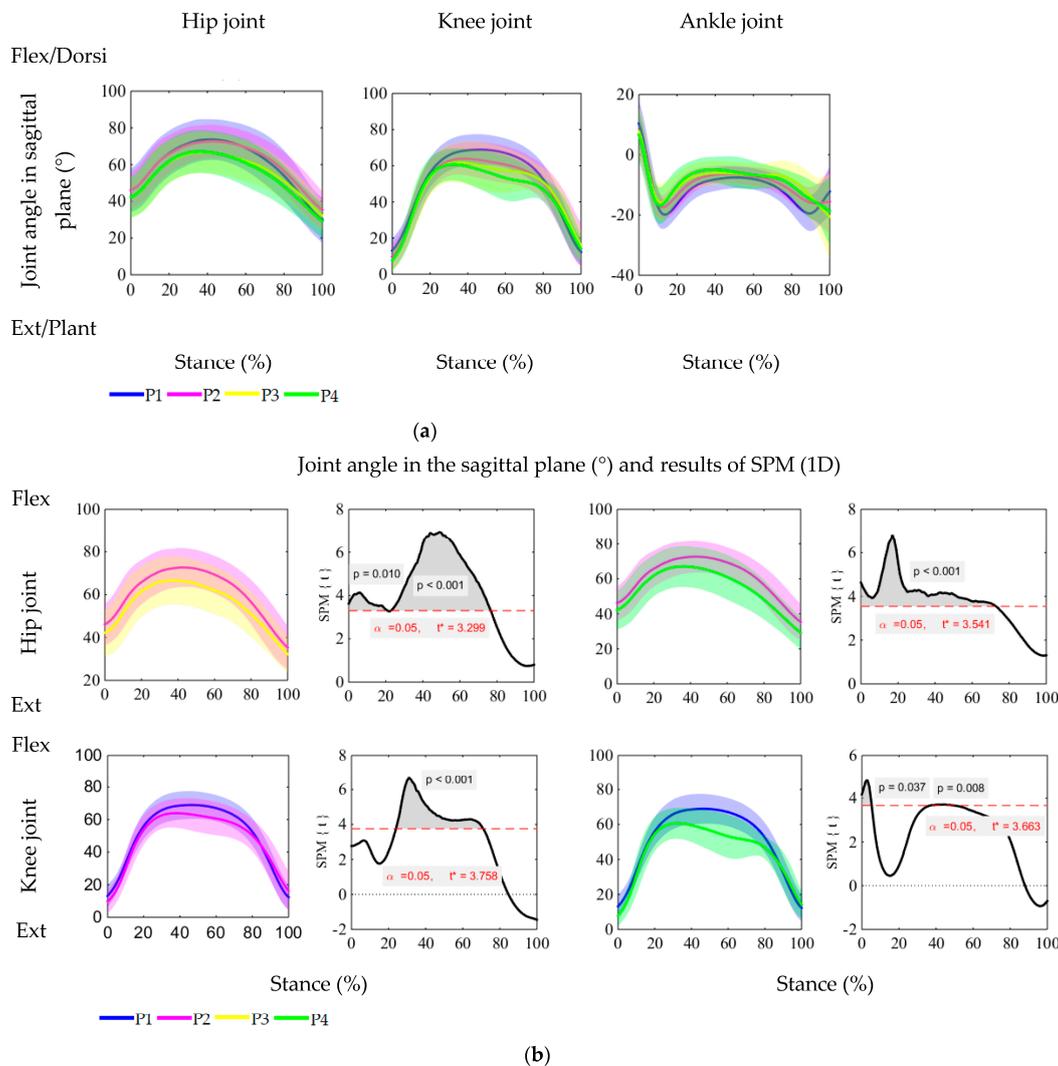


Figure 2. (a) Summary of the joint angles (mean \pm SD) of lower limbs in the sagittal plane. (b) Results with significant differences of one-dimensional statistical parametric mapping (SPM (1D)) for hip and knee joint angles. Positive angles represent hip and knee flexion and ankle dorsi-flexion. P1–P4: the 1st, 2nd, 3rd, and 4th stages of the fatiguing process, respectively.

3.6. SPM (1D) of Kinetics of Lower Extremity Joints

Figure 3 illustrates the vGRF waveform data of P1, P2, P3, and P4, and the results of SPM (1D) analysis with significant differences, which are shown mainly in the pre-drive-off phases between P1 and P4 ($p < 0.001$).

Figure 4a illustrates the waveform data of the hip, knee, and ankle joint moments and power in the sagittal plane (mean \pm SD) in P1, P2, P3, and P4. SPM (1D) analysis results of moments and power with significant differences are illustrated in Figure 4b,c, respectively. For hip and knee moments, significant differences exist in the partial period of the pre-drive-off phase (IV) between P1 and P3 ($p < 0.001$), and in the IV phase between P1 and P4 ($p < 0.001$). Moreover, Figure 4c illustrates that significant differences exist in the partial IV and drive-off (V) phases for hip power (P1 vs. P4: $p < 0.05$) and knee power (P1 vs. P3: $p < 0.001$; P1 vs. P4: $p < 0.001$).

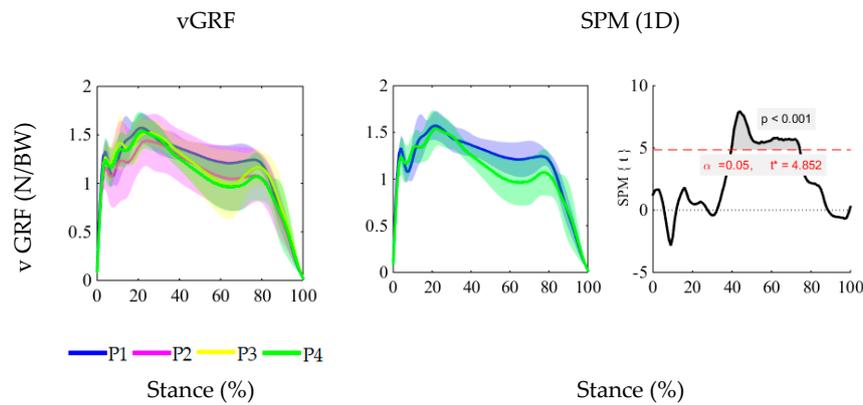
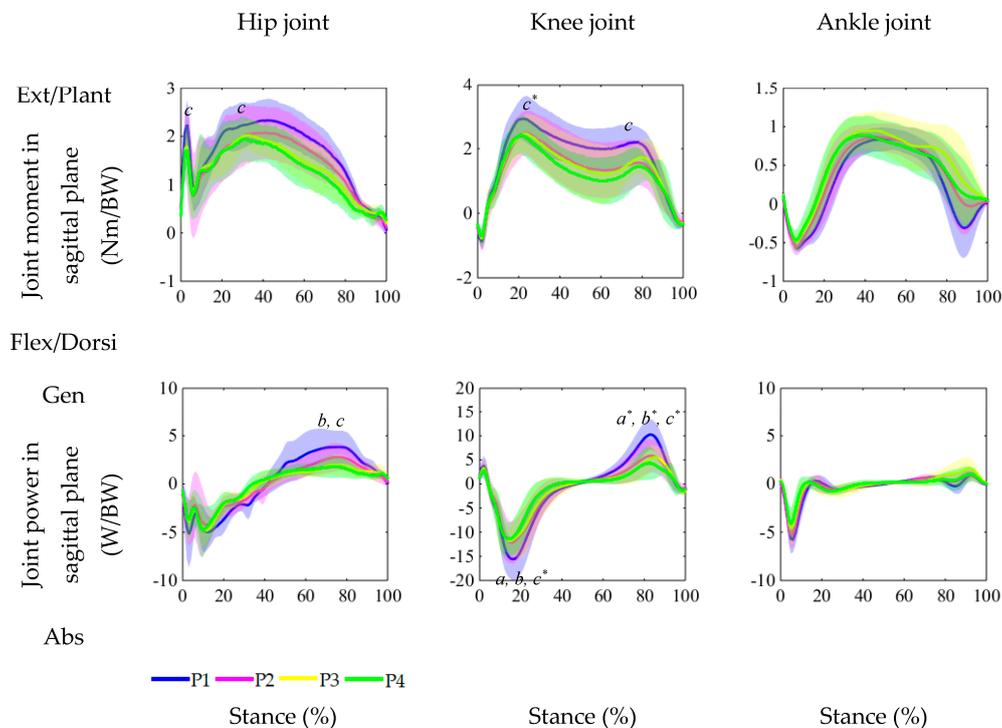


Figure 3. Vertical ground reaction force (vGRF) and results with significant differences of one-dimensional statistical parametric mapping (SPM (1D)). P1–P4: the 1st, 2nd, 3rd, and 4th stages of the fatiguing process, respectively.



(a)

Figure 4. Cont.

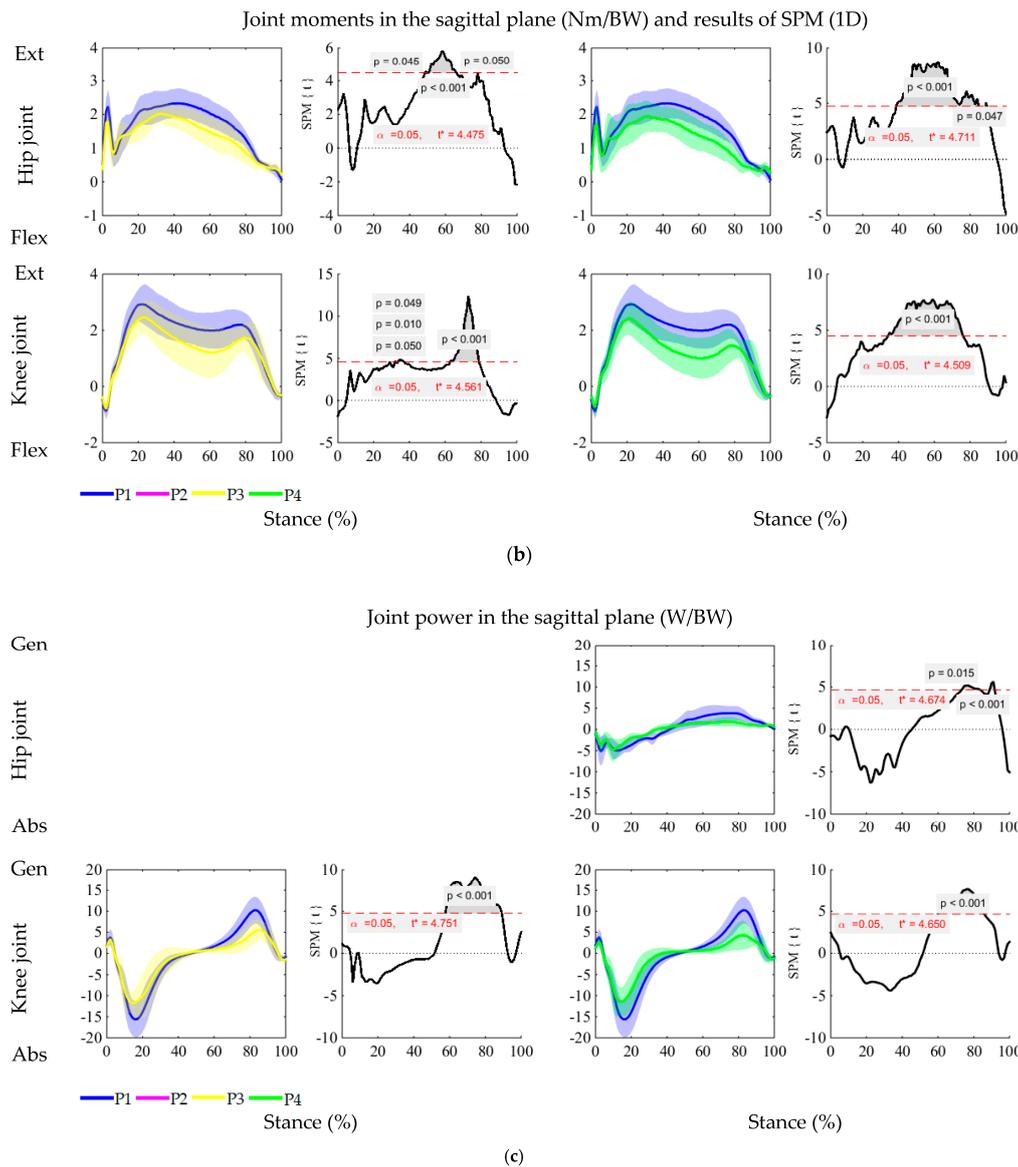


Figure 4. (a) Summary of joint moments and power (mean ± SD) of lower extremities in the sagittal plane during the lunge. (b) Results with significant differences of one-dimensional statistical parametric mapping (SPM (1D)) for hip and knee joint moments. (c) Results with significant differences of SPM (1D) for hip and knee joint power. Positive moments represent hip and knee extensor and ankle plantar flexor moments, and positive joint power indicates periods of power generation. P1–P4: the 1st, 2nd, 3rd, and 4th stages of the fatiguing process, respectively. *a*, *a**: significant differences between P1 and P2 at 0.05 and 0.01 levels, respectively; *b*: significant differences between P1 and P3 at 0.05 level; *c*, *c**: significant differences between P1 and P4 at 0.05 and 0.01 levels, respectively.

4. Discussion

An increasing number of people now play badminton. Both athletes and recreational players attempt to optimize their performance, thus increasing the risk of injury. Prevention of sports-related injuries is an important challenge. Fatigue is a major factor causing injury. Consequently, this study investigated the fatigue effects on a specific movement in badminton, i.e., the footwork associated with the lunge, which is one of the most used and integral movements [10,11].

Considering the task dependency of fatigue, a repeated forehand forward lunge, until reaching exhaustion, was proposed as the fatigue protocol, which was subdivided into four stages (P1, P2, P3, and P4) according to the slope of the heart rate (HR)–time curve. After the protocol, the mean

values of HR, blood lactate (BL), and rating of perceived exertion (RPE) increased significantly at the significance level of 0.001; in particular, the mean HR was greater than 185 beats/min, the mean BL value was greater than 14 mmol/L, and the mean RPE score was greater than 18, indicating that all participants were fatigued. At P1, the first stage of the fatigue protocol, all participants were in a pre-fatigue state and, at P4, the final stage of the fatigue protocol, they were fatigued. In addition, according to previous studies [10,20,21], the first, second, and third impact peak (PF1, PF2, and PF3) and knee flexion peak angle (PAK) were used to subdivide the lunge stance phase into initial contact (I: 0-PF1), impact loading (II: PF1-PF2), weight acceptance (III: PF2-PAK), pre drive-off (IV: PAK-PF3), and drive-off (V: PF3-end) periods. Then, statistical analyses were undertaken for both discrete and waveform kinematic and kinetic data in the sagittal plane, in which the largest movements occurred, comparing not only the pre- and post-fatigue states, but also the four stages of the fatiguing process.

The results supported the hypothesis that the biomechanical characteristics of the lunge change significantly during the fatiguing process. At the initial contact time, participants exhibited a more “erect” posture for the lunge, which is usually observed by coaches, and was shown as less hip and knee flexion, and ankle dorsi-flexion. Less dorsi-flexion at the foot strike has been found for recreational players with a relative lack of muscle power compared to national-level badminton athletes [19]. In the lateral jump performed in badminton, Herbaut et al. [27] found a decreased plantar-flexion angle at the foot strike post-fatigue. These changes may be induced by muscle fatigue caused by repeated stretch-shortening. Furthermore, the range of motion (RoM) of hip, knee, and ankle joints was decreased due to the fatiguing process.

Smaller peak joint angles were found at hip, knee, and ankle joints in the sagittal plane, particularly at the knee joint (with significant differences between P1 and the other three stages of the fatiguing process). After fatigue, a decrease in the knee peak angle was also found by Valldecabres et al. [16], however, no significant difference was found. The discrepancy may be due to the participant’s sports level [24]. The decrease in the peak angle could be explained by the decrease in joint moments (details in Figure 4). There were significant differences in peak joint moments at the hip and knee extensor (P1 vs. P4: hip ($p = 0.03$), knee ($p < 0.001$)). A similar relationship was illustrated by Fu et al. [19] between professional and amateur badminton players; that is, professional players with greater muscle strength and better performance showed higher knee and ankle joint moments. Additionally, a shorter time was taken to flex to the peak angle, with significant decreases in time shown at the knee and ankle. This may be caused by impaired control due to fatigue. This can also be explained in this study by the decrease in joint moments and power.

In addition to the angles, the durations of the four sub-stance phases (II–V) changed during the process of the fatigue protocol. The shorter durations of II and III indicate that less time was taken to reach PF2 and PAK, respectively; that is, due to the fatiguing process, the participant placed his foot flat and flexed his knee more quickly. This is consistent with the increased ankle plantar flexor and knee flexor moments in the present study (Figure 4a), and with the opinion that fatigue reduces the capacity of muscles to generate force. The most significant increase was found in the IV phase (pre-drive-off), increasing from $27.25 \pm 10.69\%$ stance to $43.38 \pm 15.24\%$ stance. Significantly decreased hip and knee peak power in this phase provided sufficient support for this change. Less power was generated for players for the drive-off. Kuntz et al. [10] indicated that a hop style lunge generates higher peak vertical force during loading. In this study, three participants used the hop style at the final stage of the fatigue protocol. The change of lunge style may be a strategy to generate more power for driving-off and returning to the starting position [14].

Furthermore, considering the time continuity of biomechanical variables of the lunge motion, one-dimensional statistical parametric mapping SPM (1D) was used to analyze the biomechanical waveform data in the sagittal plane. Most of the joint angle, moment, and power waveforms decreased consistently during the process of the fatigue protocol (among P1, P2, P3, and P4). Significant differences were found in the hip and knee joint angles, mainly in the pre-drive-off phase (IV) (most p values were less than 0.001). The results support the hypothesis that the fatigue effects were different in the five

periods of the lunge. Moreover, these results support the view that lunge characteristics change due to fatigue.

Taking into account the joint moments, both the hip and knee joints showed a significant response to the fatigue protocol. Significant differences were found between P1 and P3 in part of the period of IV, and between P1 and P4 in IV. The hip moments had a larger effective scope. However, there were only significant differences in the hip power between P1 and P4. For knee power, the significant differences were seen between P1 and P3, and also between P1 and P4, with a larger effective scope of the period. This indicates that the significant decrease in joint power occurred earlier and was mostly evident at the knee; that is, the fatigue responses manifested mostly at the knee joint. This result is consistent with a previous epidemiology study that reviewed musculoskeletal injuries among Malaysian badminton players, which reported that the majority of injuries sustained by players were due to overuse, primarily of the knee [7]. Another study [28] suggested that the rapidly changing eccentric/concentric work of the quadriceps in the varying degree of knee flexion was probably associated with patellar tendon injury. This may be why patellar tendinopathy is the most common injury of lower limbs among badminton players, and this result also supports our third hypothesis. Coaches and players should pay more attention to the training of the knee, and particularly the knee extensors.

Additionally, a comparison indicates that the discrete and waveform results are consistent. There are significant differences in CAH (P2 vs. P3), CAK (P2 vs. P4), PAK (P1 vs. P2; P1 vs. P4), knee peak moment (P1 vs. P4), hip peak power (P1 vs. P4), and knee peak power (P1 vs. P3; P1 vs. P4). In addition, significant differences were shown in these periods of stance phase in the discrete data. The results of SPM (1D) analysis clearly provided more information, indicating the period rather than a point of time in the fatigue response. This is also helpful in identifying the key body segments affected by fatigue. Thus, it is important for coaches and players to design a corresponding training program to improve the technique and muscle strength. Moreover, the results of SPM (1D) can provide support for monitoring of training.

Considering the key findings of this study, a few limitations should be noted when interpreting the results. First, the participants were male badminton players with at least 8 years of special badminton training. Results may differ for players of different levels, ages, and gender, thus studies of players with a range of abilities and ages, including female players, should be considered. Second, all tests were conducted on a simulated badminton court. Third, the sample size was limited. Fourth, the changing slope of the HR–time curve was used to subdivide the fatiguing process. However, it is not sufficient to explain the status of fatigue. Electromyography (EMG) data might be more suitable and could be used in future work. Finally, although joint moments and power allow further assessment of the functional contribution of the joints, EMG and musculoskeletal system simulations would help understand movement changes during the fatiguing process.

5. Conclusions

This study investigated the changes in the kinematic and kinetic characteristics of lunge footwork during the fatiguing process. To the best of our knowledge, this study was the first to subdivide the fatiguing process and analyze the changes among different sub-stages. It was also the first study to use one-dimensional statistical parametric mapping (SPM (1D)) to analyze the effect of fatigue on the lunge footwork in badminton. Statistically significant differences were found in both the discrete and waveform data. Moreover, these differences were shown not only between pre- and post-fatigue, but also among other sub-stages.

Overall, the results presented in this study confirm that period IV of the stance phase is more sensitive to fatigue than the other periods. In addition, the training program should focus on muscular strengthening of the knee extensor, particularly in period IV. It is also important to improve the strength of hip extensors. Furthermore, although the results show consistent changes between the discrete and waveform data, findings from this study highlight that results of SPM (1D) are more useful for the

assessment of weak areas of the body and periods of motion. This information may contribute to the future design and development of training plans and to the monitoring of training.

Author Contributions: Y.D. designed, carried out the experiments, analyzed the data and wrote the paper, Y.F. designed the experiments, reviewed and revised the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the National Natural Science Foundation of China (NSFC), grant number 11421202.

Acknowledgments: We thank Changhao Jiang from Capital University of Physical Education and Sports and Huijuan Tian from Tianjin Polytechnic University for giving suggestions for the analysis. We thank all the participants in this study.

Conflicts of Interest: The authors have no conflict of interest concerning this manuscript.

References

1. Krøner, K.; Schmidt, S.A.; Nielsen, A.; Yde, J.; Jakobsen, B.W.; Møller-Madsen, B.; Jensen, J. Badminton injuries. *Br. J. Sports Med.* **1990**, *24*, 169–172. [[CrossRef](#)] [[PubMed](#)]
2. Fahlstrom, M.; Bjornstig, U.; Lorentzon, R. Acute badminton injuries. *Scand. J. Med. Sci. Sports* **1998**, *8*, 145–148. [[CrossRef](#)] [[PubMed](#)]
3. Yung, P.S.; Chan, R.H.; Wong, F.C.; Cheuk, P.W.; Fong, D.T. Epidemiology of injuries in Hongkong elite badminton athletes. *Res. Sports Med.* **2007**, *15*, 133–146. [[CrossRef](#)] [[PubMed](#)]
4. Badminton World Federation. Players Worldwide. In Badminton World Federation [Online]. Available online: <http://smj.sma.org.sg/5011/5011a10.pdf> (accessed on 25 June 2009).
5. Weir, M.A.; Watson, A.W. A twelve month study of sports injuries in one Irish school. *Irish J. Med. Sci.* **1996**, *165*, 165–169. [[CrossRef](#)] [[PubMed](#)]
6. Herbaut, A.; Delannoy, J.; Foissac, M. Injuries in French and Chinese regular badminton players. *Sci. Sport* **2018**, *33*, 145–151. [[CrossRef](#)]
7. Shariff, A.H.; George, J.; Ramlan, A.A. Musculoskeletal injuries among Malaysian badminton players. *Singap. Med. J.* **2009**, *50*, 1095–1097.
8. Goh, S.L.; Mokhtar, A.H.; Mohamad Ali, M.R. Badminton injuries in youth competitive players. *J. Sports Med. Phys. Fit.* **2013**, *53*, 65–70.
9. Hensley, L.D.; Paup, D.C. A survey of badminton injuries. *Brit. J. Sports Med.* **1979**, *13*, 156–160. [[CrossRef](#)]
10. Kuntze, G.; Mansfield, N.; Sellers, W. A biomechanical analysis of common lunge tasks in badminton. *J. Sports Sci.* **2010**, *28*, 183–191. [[CrossRef](#)]
11. Phomsoupha, M.; Laffaye, G. The science of badminton: Game characteristics, anthropometry, physiology, visual fitness and biomechanics. *Sports Med.* **2015**, *45*, 473–495. [[CrossRef](#)]
12. Muttalib, A.; Zaidi, M.; Khoo, C. A survey on common injuries in recreational badminton players. *Malays. Orthop. J.* **2009**, *3*, 8–11. [[CrossRef](#)]
13. Kondric, M.; Matković, B.R.; Furjan-Mandić, G.; Hadžić, V.; Dervisević, E. Injuries in racket sports among Slovenian players. *Coll Antropol.* **2011**, *35*, 413–417. [[PubMed](#)]
14. Jørgensen, U.J.; Winge, S.J. Injuries in Badminton. *Sports Med.* **1990**, *10*, 59–64. [[CrossRef](#)] [[PubMed](#)]
15. Pincivero, D.M.; Aldworth, C.; Dickerson, T.; Petry, C.; Shultz, T. Quadriceps-hamstring EMG activity during functional, closed kinetic chain exercise to fatigue. *Eur. J. Appl. Physiol.* **2000**, *81*, 504–509. [[CrossRef](#)] [[PubMed](#)]
16. Valldecabres, R.; De Benito, A.M.; Littler, G.; Richards, J. An exploration of the effect of proprioceptive knee bracing on biomechanics during a badminton lunge to the net, and the implications to injury mechanisms. *Peer J.* **2018**, *6*, e6033. [[CrossRef](#)]
17. Hong, Y.; Wang, S.J.; Lam, W.K.; Cheung, J.T.M. Kinetics of badminton lunges in four directions. *J. Appl. Biomech.* **2014**, *30*, 113–118. [[CrossRef](#)]
18. Mei, Q.; Gu, Y.; Fu, F.; Fernandez, J. A biomechanical investigation of right-forward lunging step among badminton players. *J. Sports Sci.* **2017**, *35*, 457–462. [[CrossRef](#)]
19. Fu, L.; Ren, F.; Baker, J.S. Comparison of joint loading in badminton lunging between professional and amateur badminton players. *Appl. Bionics Biomech.* **2017**, *2017*, 5397656. [[CrossRef](#)]

20. Lees, A.; Hurley, C. Forces in a badminton lunge movement. In *Science and Racket Sports*; Reilly, T., Hughes, M., Lees, A., Eds.; E & FN Spon: London, UK, 1994; pp. 249–256.
21. Lam, W.K.; Ding, R.; Qu, Y. Ground reaction forces and knee kinetics during single and repeated badminton lunges. *J. Sports Sci.* **2017**, *35*, 587–592. [[CrossRef](#)]
22. Pataky, T.C. Generalized n-dimensional biomechanical field analysis using statistical parametric mappin. *J. Biomech.* **2010**, *43*, 1976–1982. [[CrossRef](#)]
23. Barber-Westin, S.D.; Noyes, F.R. Effect of fatigue protocols on lower limb neuromuscular function and implications for anterior cruciate ligament injury prevention training: A systematic review. *Am. J. Sports Med.* **2017**, *45*, 3388–3396. [[CrossRef](#)] [[PubMed](#)]
24. Roth, R.; Donath, L.; Zahner, L.; Faude, O. Acute leg and trunk muscle fatigue differentially affect strength, sprint, agility, and balance in young adults. *J. Strength Cond. Res.* **2019**. [[CrossRef](#)] [[PubMed](#)]
25. Borg, G.A.V. Psychophysical bases of perceived exertion. *Med. Sci. Sports Exerc.* **1982**, *14*, 377–381. [[CrossRef](#)] [[PubMed](#)]
26. Cappozzo, A.; Catani, F.; Della Croce, U.; Leardini, A. Position and orientation in space of bones during movement: Anatomical frame definition and determination. *Clin. Biomech.* **1995**, *10*, 171–178. [[CrossRef](#)]
27. Herbaut, A.; Delannoy, J. Fatigue increases ankle sprain risk in badminton players: A biomechanical study. *J. Sports Sci.* **2020**, *38*, 1560–1565. [[CrossRef](#)]
28. Peers, K.H.; Lysens, R.J. Patellar tendinopathy in athletes: Current diagnostic and therapeutic recommendations. *Sports Med.* **2005**, *35*, 71–87. [[CrossRef](#)]

Publisher’s Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).