Impaired Performance of the Smash Stroke in Badminton Induced by Muscle Fatigue

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Original investigation

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Running head : Fatigue and badminton smash stroke.

Abstract : 219 words

Text : 3462 words

Figures : 2 ; Tables : 2

Muscle fatigue impairs the performance of the smash stroke in badminton

Abstract

Purpose: The main aim of the present study was to evaluate the effects of muscle fatigue on badminton performance during a smash stroke. **Methods:** Seventeen young well-trained players completed twenty forehand smash twice (pre and post fatigue protocol) and both speed and precision of the strokes were measured. The fatigue protocol consisted in ten series of ten maximal counter movement jump (CMJ, 3 s rest in-between) followed by eight lunges. Perception of effort and CMJ performance during each series were also measured to assess fatigue. **Results:** Shuttlecock speed decreased moderately (-3.3%) but significantly after the fatigue protocol ($P<0.001$, $\eta_{p2}=0.671$). Precision significantly decreased after the fatigue protocol (-10.3%, $P=0.001$, $\eta_{p2}=0.473$). The decrease in precision was mainly due to an increased number of faults ($P=0.006$, $\eta_{p2}=0.378$, $d_z=0.756$) and to a decrease in accuracy ($P=0.066$, $\eta_{p2}=0.195$, $d_z=0.478$). **Conclusion:** The present study showed that fatigue impairs the performance during specific badminton skills. Moreover, by showing a slight decrease in speed and a large decrease in accuracy of the shuttlecock when fatigue is experienced, the present study suggested that, as previously observed in other racket sports, the speed of the missile appears to be the key factor used by the players to win the rally. Coaches and physical trainers should therefore develop intervention aiming to limit the negative impact of fatigue on badminton strokes.

Keywords: sport motor skills, racket sports, speed, accuracy

INTRODUCTION

As a racket sport, it is well-known that performance in badminton is multifactorial including physiological psychological, technical and/or tactical parameters[1]. However, the impact of each of these parameters on the ability to perform at high-level is still a matter of debate. For instance, Ooi et al.[2] did not observe differences between elite and sub-elite Malaysian players when performing a battery of physical performance tests, suggesting that other factors, such as technical skills, were possibly of more importance[2]. This finding is also supported by Chin et al.[3], who found a low correlation between a specific aerobic field-test and the ranking of the players. By contrast, Phomsoupha and Laffaye[4] showed that the speed of the shuttlecock evolved linearly with the level of the players, allowing to differentiate high-skilled and elite players. Similarly, Sakurai and Ohtsuki[5] showed that the probability of hitting a target, i.e. accuracy, was greater for the skilled players when compared to unskilled.

Neuromuscular fatigue, which can be defined as a loss of force (or power) production capacity accompanied by an increase in the effort required to perform the exercise[6] generally occurs during physical activity. As previously observed in other racket sports[7,8], neuromuscular fatigue, demonstrated by a reduction of maximal voluntary contraction force, has been also reported after 1-h of a simulated badminton game (-11% and -18% for the knee extensors and the knee flexors, respectively)[9]. Due to the high influence of technical parameters on performance in badminton, it is of critical importance to evaluate the impact of muscle fatigue on specific motor skills, which appears to be the most relevant parameters at high level[2,3]. In the setting of goal-directed movement assessed during racket sports, both speed and precision of the projectile are the two relevant technical parameters to describe the quality of a stroke[4,10,11]. To date, very few studies have attempted to emphasize the paradigm between the movement speed and the movement precision, i.e., speed-accuracy trade-off[12], during the same task in a non-fatigued and fatigued condition during racket sports[10,11,13].

Missenard et al.[14] showed that muscle fatigue (elbow flexors and extensors) impaired a pointing task by increasing the movement duration to guarantee task success, i.e., precision. From an ecological aspect, several studies have previously investigated the impact of muscle fatigue on specific sport motor skills by measuring simultaneously these parameters during racket sports. These studies demonstrated that precision is largely affected in fatigued condition in tennis[11] and table tennis[15] whereas ball speed is less deteriorated. However, this result was not systematic[13]. To the best of our knowledge, no study has attempted to evaluate the impact of muscle fatigue on sport motor skills during a specific badminton task.

This study aimed therefore to evaluate the impact of muscle fatigue on badminton-specific technical performance. To do that, we have first developed a field test to evaluate the reliability for both precision and shuttlecock speed during a smash stroke, which is classically considered as the most powerful stroke, generally used for winning the rally[16] (Study 1). Thereafter, this test was performed before and after a fatiguing protocol (Study 2) to measure in what extent fatigue could impair the speed and/or the accuracy of the shuttlecock during a specific badminton stroke.

METHODS

Participants

Fifty-five participants (mean ± SD age: 22.7 ± 5.7 yr; height: 179.9 ± 6.9 cm; mass: 71.9 ± 6.2 kg) volunteered to participate in this study. All participants or legal representatives for minors gave their written consent after being informed about the procedures of the protocols, which were approved by local ethics committee of Nantes, in accordance with the Declaration of Helsinki. Among these players, thirty-eight (males only, mean ± SD age: 25.3 ± 5.0 yr; height: 181.2 ± 5.5 cm; mass: 74.1 ± 4.8 kg) participated in Study 1, i.e., reproducibility of the specific test, and seventeen (M=11, F=6, 17.0 ± 0.8 yr, 177.0 ± 8.8 cm, 67.1 ± 6.4 kg) participated in Study 2, i.e., effects of muscle fatigue on badminton-specific technical performance.

Study design

Study 1

Players were divided into four groups according to their single ranking in the French Federation of Badminton (FFBad) and their training volume (Table 1). In the high trained group (HT, n=9), all players were high-trained (4.9 ± 1.3 times per week) and participated in national competitions. In the moderate trained group (MT, n=10), players were moderate to well-trained (3.1 ± 1.0 times per week) and participated in a regional championship. In the low trained group (LT, n=9), players were less trained (2.0 ± 0.7 times per week) and participated in a local championship. The untrained group (UT, n=10) was composed by sports-science-students, without experience in badminton and not ranked by the FFBad.

After a 15-min standardized warm-up and once familiarized (10 trials) with the procedures, all the participants performed one session which consisted of performing the specific test (see specific test) twice (intra-session reliability), with a 10-min resting period in between. Thirty-three participants, among the 38 participants initially recruited, participated in a second session to assess the inter-session reliability. A minimum of 7 days interval was defined between both sessions.

Study 2

All participants (n=17) were recruited from French National badminton training centers and were well-trained (15.5 ± 1.8 $h.wk^{-1}$), regularly participated in national competitions in the French championship, and none of them had any known muscle/tendon injury for at least one year. One session (duration: ~ 45 min) was performed to assess the effects of muscle fatigue on badminton-specific technical performance. All sessions took place in a homologated specific facility comprising two courts. All participants were familiarized with all procedures at the beginning of the session. Before and immediately after (~30 s) completion of the fatigue protocol (see below for further details) participants performed the specific badminton test (see specific test) to measure the quality (precision and speed of the shuttlecock) of the smash. To control for the effect of the fatiguing protocol, both subjective (perception of effort) and objective (maximal height during a countermovement jump [CMJ]) measurements of fatigue were assessed.

We quantified badminton-specific technical performance by measuring stroke parameters during the specific test previously described (Study 1). The test took place in a second court, close to the one used during the fatigue protocol. To take into account the ecological aspects of badminton smash[17], male players were asked to jump when performed the stroke while this rule was not mandatory for the female players.

Specific test

The test consisted in 20 forehand overhead smash, which is considered as a typical offensive stroke. They were asked to hit, alternatively, two targets placed on the court (Fig 1A). The 2 rectangular targets (212 cm length/40 cm width) were positioned on the sides and were divided into 2 areas (212 cm length/20 cm width; Fig 1A). The players were instructed to hit the shuttlecock (Aerosensa 50, Yonex®, Tokyo, Japan) for winning the rally as they do during an official game. Ten trials were evaluated for each target. The shuttlecock was sent by a robot (BKL, Badenko®, Pampelonne, France) to ensure protocol standardization and repeatability for shuttlecock speed, trajectory and placement. For each trial, the robot sent the shuttlecock to the center of the court, placing it 75-80 cm away from the baseline (Fig 1A). The shuttlecock was delivered by the robot every 3 s with a rising trajectory. New shuttlecocks were used for each session and were replaced when they were damaged.

The performance assessment was explained to the participants before starting the test. During the test, participants were strongly encouraged and informed on their outcome in order to maintain vigilance and concentration throughout the procedure.

Muscle fatigue

To induce muscle fatigue (study 2), participants completed 10 series of two specific movements frequently used by the badminton players, i.e., CMJ[17] and lunges[9,17,18]. Each series consisted of ten CMJ performed every 3 s. CMJ were realized hands akimbo, and subjects were asked to perform each trial maximally. Once the CMJ performed, subjects kept their own racket and had to realize 8 lunges with no rest between the two exercises. During the lunges task, participants were asked to touch alternatively the right and the left parts of the net with their racket (1-m width). Between two lunges, participants moved 1-m behind the short service line before continuing the exercise (Fig 1B). Once the exercise completed, subjects came back walking (10-s) to the baseline, rated their perceived exertion, and started a new series, until 10 series were performed. During the last series, subjects only performed 10 CMJ, without execution of lunges to better assess the fatigue induced by our protocol, since CMJ represents the objective measure of fatigue used in this study. The instruction was given to the players to directly move on the badminton test after the last series of CMJ. This protocol was chosen to induce a level of fatigue consistent with the one observed during a real badminton game. We assume that it represented a good compromise, taking into account the duration of the protocol (~7 min), the number of lunges and jumps performed[9]. To maintain motivation, subjects were strongly encouraged during the entire protocol.

Data processing

Shuttlecock speed

For each smash, the speed of the shuttlecock hit by the player was measured with a radar (Stalker ATS ii, Stalker Radar®, Plano, Texas, USA) at a frequency of 50 Hz and an accuracy of ± 0.041 $m.s^{-1}$. The radar was located 3 m behind the player, at a height of 2.50 m[4]. To ensure recording of the speed data, an experimenter manually pointed the radar towards the area targeted by the player. All data were recorded on a personal laptop (software: Stalker ATS 5.0, Plano, Texas, USA). The shuttlecock speed for each of the 20 smashes was measured. The mean speed was then calculated by averaging the 20 speed values.

Precision

The evaluation of precision was assessed by using a video camera (AHD-H12 VAZ2S, Aiptek®, Rowland Street, Ca, USA) for post-processing analysis. The camera was located 5 m behind the baseline opposite to the player and in the axis of the radar and the robot (Fig 1A). The following procedure was used: when the shuttlecock reached the part of the target nearest from the sideline, 3 points were granted (i.e., accuracy); 2 points when the shuttlecock reached the part of the target furthest from the sideline (i.e., consistency); 1 point when the shuttlecock reached the court but did not touch the targets (i.e., neutral); 0 point when a fault was committed (Fig 1A). This procedure gave a score between 0 and 60 for each series.

Perception of effort (RPE). In study 2, perception of effort, defined as "the conscious sensation of how hard, heavy, and strenuous the physical task is"[20] was measured throughout the fatigue protocol. Participants were asked to rate the effort related to the physical task just performed by using the 6-20 Borg Scale[21] after the first nine series.

CMJ. In study 2, optojump photoelectric cells (Microgate, Bolzano, Italy) were used to precisely measure the jump height[22]. Fatigue was assessed by calculating the average of the height of the 10 CMJ performed from each series. We also compared CMJ performance between the average of the first three CMJs of the first series (trials 1-3) and the last three CMJs of the last series (trials 98-100). All data were recorded on a personal laptop with the appropriate software (Optojump software, version 3.01.0001) for further treatment.

Statistical analysis

Statistical tests were performed with Statistica®V6 software (Statsoft, Tulsa, USA) and G*Power® software (version 3.1.6 Universität Düsseldorf, Germany). Assumptions of normality (Kolmogorov-Smirnov test) and sphericity (Mauchly test) of data were checked as appropriate. Values are presented as mean ± SD.

Study 1

Speed and precision were compared across the four populations by using a one-way analysis of variance (ANOVA) (4 between-subjects factors) for the first series of the first day. Correlation analyses (Bravais-Pearson) were performed to determine whether speed, precision, or performance index were correlated to the skill level (i.e., FFBad ranking). For each group, standard error of measurements (SEM), intraclass correlation coefficients (ICC) and coefficient of variation (CV) were calculated for both intra-day and inter-day[23]. Since we used a set time between sessions, the ICC (3, 1) was chosen from Shrout and Fleiss[24]. Inter-day reliability was assessed by using the first series of day 1 *vs.* the first series of day 2.

Study 2

RPE and CMJ height were tested using one-factor (time) ANOVA with repeated measures. Stroke smash parameters (speed and precision) and the distribution, i.e., percentage of faults, neutral, consistency and accuracy, were then tested with one-way (time) ANOVA.

In both studies, the level of significance was set at $P<0.05$ and post-hoc analyses were performed when appropriated using HSD Tukey test for multiple comparisons. For the main effects of the ANOVAs, partial eta square (η_{p2}) are reported, with moderate and large effects considered for $\eta_{p2}\geq0.07$ and ≥0.14, respectively[25]. For the follow up tests, Cohen's effect sizes *d* are reported, with small, moderate and large effects considered for $d \geq0.2$, ≥0.5 and ≥0.8, respectively[25].

RESULTS

Study 1

Effect of expertise on performance factors

Shuttlecock speed

Our results showed a significant effect of expertise ($\eta_{p2}=0.954$; $P<0.001$). Shuttlecock speed was higher for HT (158.1 ± 5.5 $km.h^{-1}$) compared to MT, LT and UT (136.4 ± 4.0 $km.h^{-1}$, 121.0 ± 4.2 $km.h^{-1}$ and 101.7 ± 5.3 $km.h^{-1}$, *d* ranged from 4.51 to 10.44, respectively; $P<0.001$), for MT compared to LT and UT (*d* ranged from 3.79 to 7.42, respectively, $P<0.001$), and LT compared to UT ($d=4.04$, $P<0.001$). In addition, a significant correlation was observed between the speed of the shuttlecock and the ranking of the player ($r=-0.81$; $P<0.001$; $n=28$, UT excluded).

Precision

A significant main effect was observed for precision (η_{p2}=0.849; P<0.001), showing that the score of precision (/60) was higher for HT (33.1 ± 2.5) compared to MT, LT and UT (26.1 ± 2.4, 21.3 ± 1.7 and 18.4 ± 3.0, *d* ranged from 2.86 to 5.52, respectively; P<0.001), for MT compared to LT and UT (d ranged from 2.26 to 2.85, respectively; P=0.001 and P<0.001, respectively). A significant correlation was also found between precision and ranking of the players (r=- 0.78; P<0.001; n=28, UT excluded).

Intra- and inter-session reliability

The mean values, SD, ICC, SEM and CV are shown in Table 2 for intra- and inter-session reliability for each group. Low CV were found for HT among all parameters, with low to high ICC. The CV for MT group were also acceptable for all variables and low to high ICC were also observed. The CV for LT were acceptable, and low to high ICC were found. Except for the speed of the shuttlecock, CV were generally higher for UT for intra- and inter-session, as well as ICC varied widely depending on the parameter considered.

Study 2

Effects of the fatigue protocol

Perception of effort.

There was a significant effect of time on the perceived exertion (P<0.001, η_{p2}=0.852). RPE progressively increased throughout the fatigue protocol (from 12.0 ± 1.7 after the first series to 18.8 ± 0.8 after the 9^{th} series).

CMJ height.

There was a main effect of time on the height performed during the CMJ (-10.1 ± 6.8%, P<0.001, η_{p2}=0.468, Fig 2). The best performance was measured after the first series (32.4 ± 4.6 cm) while the weakest performance was measured after the last series (29.0 ± 4.0 cm). The greatest difference was observed between the first three CMJs of the first series (32.9 ± 4.6 cm) and the last three CMJs of the last series (27.4 ± 4.5 cm), i.e. -16.9 ± 9.8% (d_z=1.692, Fig 2).

Effects of muscle fatigue on badminton performance

Shuttlecock speed.

There was a significant effect of time for the shuttlecock speed (P<0.001, η_{p2}=0.671). This parameter decreased about 3.3 ± 2.4% in the fatigued state, from 151.2 ± 4.6 km.h^{-1} to 146.2 ± 3.9 km.h^{-1} (Fig 3A).

Total score.

There was a significant effect of time for the total score (P=0.001, η_{p}^{2}=0.473). This parameter decreased about 10.3 ± 10.3% in the fatigued state, from 27.4 ± 5.9 to 24.4 ± 4.7 (Fig 3B).

Distribution.

There was a main effect of time on the number of faults committed by the players (from 29.7 ± 13.3% to 37.9 ± 11.6%, P=0.006, η_{p}^{2}=0.378, d_z=0.756). There was no main effect of time on consistency (from 19.7 ± 13.0% to 20.0 ± 10.2, P=0.918, η_{p}^{2}=0.0006, d_z=0.026) while a clear trend was observed for accuracy, with small to moderate effect size (from 23.5 ± 8.8% to 19.7 ± 6.0%, P=0.066, η_{p}^{2}=0.195, d_z=0.478, Fig 3C).

DISCUSSION

The main outcomes of the present study showed that the quality of the smash was impaired by muscle fatigue. The speed of the shuttlecock slightly decreased while the precision substantially decreased after the fatigue protocol.

Specific test

The results of our study 1 demonstrated that the test proposed herein (i) is sensitive enough to discriminate groups or players with different playing levels, (ii) shows that, when the shuttlecock parameters (speed and precision) are assessed simultaneously, they are both correlated with the ranking of the player and (iii) is highly reliable (intra and intersession) when high trained players are considered, as used in study 2. Specifically, as regards shuttlecock speed, we observed high ICC for all groups (around 0.8 for intra-session reliability), whereas ICC varied from low to very-low (ranged from 0.15 to 0.42) for the precision. However, a low between-subject variability is known to decrease ICC[23,26,27]. In the current study, we observed a very small intra-session variability for both high and moderate trained groups (i.e. SD ranged from 1.2 to 2.5). As both CV and SEM were low, we considered that the test proposed herein was consistent for the players who exhibited sufficient technical skills. Thus, the use of this specific test was relevant to assess the effects of fatigue on the quality of the smash parameters.

Markers of fatigue

Psychological marker. The perceived exertion regularly increased throughout the fatigue protocol, showing that the players were close to exhaustion before performing the second badminton test. Although it should be kept in mind that RPE measured during official junior games is less than that induced in the current study (~14.5 *vs* 18.8)[19], it is plausible that after a particularly challenging rally, the perceived exertion is significantly greater than that measured at the end of the game. Thus, Abian et al.[28] showed that in the modern badminton, the rally duration tends to increase, as well as the recovery between two rallies, reflecting a more demanding physical condition. Therefore, although the perceived exertion measured at the end of the fatigue protocol was very high, we assume that such a fatigue may occasionally exist during badminton game.

Physical marker. The increase in perceived exertion was accompanied by a significant decrease in performance to perform CMJ (-10.1 ± 6.8%). This decrease was mainly due to the repetition of lunges and CMJ without rest during ~7 min, which could have induced muscle damage. Abian-Vicen et al.[29] have previously shown that performance in CMJ decreased over time during successive badminton games (-7.2%, $P<0.05$), although no effect was reported after only one game.

Taken together, both subjective and functional parameters, allow to conclude that the fatigue protocol successfully induced a state of fatigue in our subjects.

Fatigue impairs specific badminton skill

In the current study, we observed that fatigue phenomenon, assessed by both subjective (increased RPE) and functional (decreased CMJ performance) parameters, induced a moderate but significant decrease of the speed of the shuttlecock during a smash stroke (-3.3 ± 2.4%). Such a result has previously been reported in tennis[13] while Le Mansec et al.[15] did not found any decrease of this parameter after both upper and lower limb fatigue during table tennis stroke. Yet, by reporting significant differences in shuttlecock speed during the smash stroke depending on the level of the players, previous[4] and current (Study 1) studies demonstrated that this parameter was very discriminant to perform at a high level during a badminton game. Thus, despite their fatigue level, the players tried to maintain, consciously or unconsciously, a high shuttlecock speed during the second specific test.

We also found that the precision was significantly decreased during the second badminton specific test, i.e., after the fatigue protocol. This decrease in precision was mainly due to an increase in the number of faults and, to a lesser extent, to a decrease in accuracy. Thus, although Missenard et al.[14] showed that during a pointing task, fatigued participants decreased the speed of their movement in order to maintain their task success, the present study gave evidence that, during a specific badminton motor skill, players have given priority to the speed of the shuttlecock, even if this led to commit more faults or reach the target less often. This result has already been observed in racket sports such as tennis[11] and table tennis[15].

How fatigue impairs stroke performance during badminton smash?

Since the design of the current study was mainly descriptive, we did not have access to the underlying mechanisms, which were able to explain the results observed. However, based on previous studies, we can advance some hypotheses. Indeed, Sakurai and Ohtsuki[5] showed that high skilled badminton players had consistent motor program, i.e., reliability of the muscle activity pattern, when they performed badminton smash. This ability to perform consistently results in a lower unforced errors[5], which has a great influence in winning or losing the game[30]. However, the coordination may be affected and a shift in motor control can be observed when fatigue is experienced, leading to conflicting results[11,31,32]. For instance, despite changes in technical factors induced by muscle fatigue, speed and accuracy were unchanged during a specific water polo motor skill[32]. As regards table tennis, Aune et al.[31] suggested that, when fatigued, high skilled players adjusted the motor coordination strategy to maintain accuracy, as explained by Missenard et al.[14]. Conversely, Rota et al.[11] showed that fatigue in upper limb muscles induced a decrease in forehand stroke accuracy associated with changes in muscle activation level, while the speed of the ball was maintained. Even if muscle activation was not measured in the current study, it might be speculated that changes in the level of activation of fatigued muscles could partly explain our results. However, further studies are required to better understand the biomechanical origins (e.g. muscular coordination pattern) of the decrease in smash stroke performance observed herein.

It is classically accepted that the temporal structure, the notational analysis or the physiological characteristics may vary depending on the gender, suggesting a higher demand during the games for males[17]. This aspect is reinforced by the study of Fernandez-Fernandez et al.[19], who showed that the activity pattern of the match is different between young males and young females players (16 yr), but induced only slight different physiological responses, i.e. same heart rate, blood lactate response, RPE. Consequently, it could be possible that the protocol used in the present study to induce fatigue may affect female players in a different manner than male players and change our results. However, no gender differences appeared for the markers of fatigue (RPE: 18.9 ± 0.7 *vs* 18.6 ± 1.0; CMJ: -10.4 ± 4.6% *vs* -9.4 ± 10.3% for males and females, respectively). Similarly, no gender difference was observed for the decrement in speed of the shuttlecock (-3.4 ± 2.0% vs -3.0 ± 3.1%). Only the decrease of the precision was different, i.e. greater for males (-13.2 ± 8.0%), when compared to females (-

5.1 ± 12.7%), possibly due to the fact that females do not jump for smash. Taken as a whole, gender seems to have a little influence on our results.

Practical applications

The results of the current study, i.e., decrease in both speed (moderate) and precision (large effect) of the shuttlecock following a fatiguing protocol, are relevant for coaches and physical trainers, since the number of unforced errors is an important factor to win the game[30] and the speed of the missile is also determinant to perform at high level[4]. Thus, coaches, physical and/or mental trainers should accustom badminton players to experience fatigue during training and to propose relevant training programs in order to minimize the magnitude of the deleterious effect of fatigue during the game.

CONCLUSION

This study highlighted that fatigue impairs the quality of the stroke performance in badminton, by altering the speed (~3%) and the precision (~10%) of the shuttlecock. Moreover, our results suggest that badminton coaches should improve the physical state of their athletes to postpone the negative effects of fatigue on specific technical skills.

Acknowledgments

The study was supported by grants from the French Ministry of Sports (contract no. 15r16). The authors thank Claude Leveau for his precious advices and Olivier Bime and the French Badminton Federation (FFBad) as well as Mourad Amrani, Frederic Pottier, the League of Badminton of Pays de la Loire and Badenko® for her material and human assistance. The authors also thank all the badminton players.

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Table caption

Table 1. Anthropometric values and badminton experience for untrained (UT), low trained (LT), moderate trained (MT) and high trained group (HT) for the participants of study 1. Values are mean ± SD.

	UT	LT	MT	HT
n	10	9	10	9
Age (years)	19.2 ± 0.8	30.3 ± 3.9	27.4 ± 2.8	24.8 ± 2.9
Height (cm)	183.9 ± 5.8	179.1 ± 4.6	178.2 ± 5.3	183.4 ± 3.9
Body mass (kg)	70.4 ± 3.0	77.7 ± 5.5	73.2 ± 3.7	75.4 ± 4.2
Badminton experience (years)	/	13.5 ± 3.5	18.3 ± 2.9	17.0 ± 3.1
Training volume ($h.w^{-1}$)	/	3.2 ± 1.3	5.5 ± 2.3	8.4 ± 1.3
Ranking (FFBad)	/	7440.3 ± 2144.7	1782.4 ± 539.0	196.0 ± 133.8

Dependent variables	Intra-session reliability						Inter-session reliability					
	n	Mean value (SD)		ICC	Mean CV (SD)	SEM	n	Mean value (SD)		ICC	Mean CV (SD)	SEM
		T1	T2					T1	T3			
HT	9						9					
Shuttlecock speed (km.h-1)		158.1 ± 5.5	159.0 ± 6.3	0.81	1.7 ± 0.5	3.0		158.1 ± 5.5	159.9 ± 7.1	0.63	2.4 ± 0.8	4.2
Precision (/60)		33.1 ± 2.5	32.2 ± 1.3	0.18	4.8 ± 3.0	1.8		33.1 ± 2.5	32.7 ± 2.6	0.62	3.8 ± 3.4	1.7
MT	10						8					
Shuttlecock speed (km.h-1)		136.4 ± 4.0	138.5 ± 5.0	0.86	1.6 ± 0.6	1.9		136.4 ± 3.4	138.6 ± 4.4	0.48	2.3 ± 0.6	3.0
Precision (/60)		26.1 ± 2.4	25.6 ± 1.2	0.15	6.3 ± 2.2	1.8		25.5 ± 2.3	24.8 ± 3.2	0.48	7.9 ± 3.6	2.2
LT	9						6					
Shuttlecock speed (km.h-1)		121.0 ± 4.2	123.3 ± 4.8	0.81	2.1 ± 0.6	2.2		122.8 ± 3.8	123.8 ± 4.9	0.33	2.8 ± 0.8	3.8
Precision (/60)		21.3 ± 1.7	21.7 ± 2.8	0.30	8.6 ± 3.6	2.0		20.7 ± 1.8	23.7 ± 1.0	0.53	9.7 ± 5.2	1.1
UT	10						10					
Shuttlecock speed (km.h-1)		101.7 ± 5.3	102.1 ± 6.2	0.78	2.4 ± 1.4	3.0		101.7 ± 5.3	102.8 ± 9.2	0.63	4.0 ± 2.3	4.9
Precision (/60)		18.4 ± 3.0	18.6 ± 3.4	0.42	12.2 ± 7.3	2.5		18.4 ± 3.0	17.4 ± 2.2	-0.14	14.1 ± 4.6	2.7

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Table 2. Intra- and inter-reliability for shuttlecock speed and precision for high trained (HT), moderate trained (MT), low trained (LT) and untrained group (UT). T1: average of the first series of the first session. T2: average of the second series of the first session. T3: average of the first series of the second session. ICC: intraclass correlation coefficient; CV: coefficient of variation; SEM: standard error of measurement. Values are mean ± SD.

Figure captions

Figure 1. Top view of the device used during the specific test (panel A). The black cross represents the position of the player to hit the shuttlecock. Black areas represent "accuracy" (3 pts) and grey areas represent "consistency" (2 Pts). Top view of the device used to induce fatigue (panel B). The grey square represents the replacement of the player after each lunge.

Figure 2. Height of the 100 countermovement jumps of the fatiguing protocol (10 sets of 10 repetitions). *** significant difference between set 1 and the other sets ($P<0.001$, mean height of the sets). Data are presented as means ± SD.

Figure 3. Effects of muscle fatigue on smash stroke parameters related to the badminton performance test: ball speed (panel A), precision (panel B) and distribution (panel C). ** and *** significant differences between pre fatigue and post fatigue ($P<0.01$, $P<0.001$, respectively). † trend difference between pre and post ($0.05<P<0.1$). Data are presented as means ± SD.