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

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1 Original investigation

2 **Impaired performance of the smash stroke in**
3 **badminton induced by muscle fatigue**

4
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25
26 **Running head :** Fatigue and badminton smash stroke.

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30

31 **Muscle fatigue impairs the performance of the smash stroke**
32 **in badminton**

33 **Abstract**

34 **Purpose:** The main aim of the present study was to evaluate the
35 effects of muscle fatigue on badminton performance during a
36 smash stroke. **Methods:** Seventeen young well-trained players
37 completed twenty forehand smash twice (pre and post fatigue
38 protocol) and both speed and precision of the strokes were
39 measured. The fatigue protocol consisted in ten series of ten
40 maximal counter movement jump (CMJ, 3 s rest in-between)
41 followed by eight lunges. Perception of effort and CMJ
42 performance during each series were also measured to assess
43 fatigue. **Results:** Shuttlecock speed decreased moderately (-
44 3.3%) but significantly after the fatigue protocol ($P < 0.001$,
45 $\eta_p^2 = 0.671$). Precision significantly decreased after the fatigue
46 protocol (-10.3%, $P = 0.001$, $\eta_p^2 = 0.473$). The decrease in
47 precision was mainly due to an increased number of faults
48 ($P = 0.006$, $\eta_p^2 = 0.378$, $d_z = 0.756$) and to a decrease in accuracy
49 ($P = 0.066$, $\eta_p^2 = 0.195$, $d_z = 0.478$). **Conclusion:** The present study
50 showed that fatigue impairs the performance during specific
51 badminton skills. Moreover, by showing a slight decrease in
52 speed and a large decrease in accuracy of the shuttlecock when
53 fatigue is experienced, the present study suggested that, as
54 previously observed in other racket sports, the speed of the
55 missile appears to be the key factor used by the players to win
56 the rally. Coaches and physical trainers should therefore develop
57 intervention aiming to limit the negative impact of fatigue on
58 badminton strokes.

59

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

61

62 INTRODUCTION

63 As a racket sport, it is well-known that performance in
64 badminton is multifactorial including physiological
65 psychological, technical and/or tactical parameters¹. However,
66 the impact of each of these parameters on the ability to perform
67 at high-level is still a matter of debate. For instance, Ooi et al.²
68 did not observe differences between elite and sub-elite
69 Malaysian players when performing a battery of physical
70 performance tests, suggesting that other factors, such as
71 technical skills, were possibly of more importance². This finding
72 is also supported by Chin et al.³, who found a low correlation
73 between a specific aerobic field-test and the ranking of the
74 players. By contrast, Phomsoupha and Laffaye⁴ showed that the
75 speed of the shuttlecock evolved linearly with the level of the
76 players, allowing to differentiate high-skilled and elite players.
77 Similarly, Sakurai and Ohtsuki⁵ showed that the probability of
78 hitting a target, i.e. accuracy, was greater for the skilled players
79 when compared to unskilled.

80 Neuromuscular fatigue, which can be defined as a loss of force
81 (or power) production capacity accompanied by an increase in
82 the effort required to perform the exercise⁶ generally occurs
83 during physical activity. As previously observed in other racket
84 sports^{7,8}, neuromuscular fatigue, demonstrated by a reduction of
85 maximal voluntary contraction force, has been also reported
86 after 1-h of a simulated badminton game (-11% and -18% for the
87 knee extensors and the knee flexors, respectively)⁹. Due to the
88 high influence of technical parameters on performance in
89 badminton, it is of critical importance to evaluate the impact of
90 muscle fatigue on specific motor skills, which appears to be the
91 most relevant parameters at high level^{2,3}. In the setting of goal-
92 directed movement assessed during racket sports, both speed and
93 precision of the projectile are the two relevant technical
94 parameters to describe the quality of a stroke^{4,10,11}. To date, very
95 few studies have attempted to emphasize the paradigm between
96 the movement speed and the movement precision, i.e., speed-
97 accuracy trade-off¹², during the same task in a non-fatigued and
98 fatigued condition during racket sports^{10,11,13}.

99 Missenard et al.¹⁴ showed that muscle fatigue (elbow flexors and
100 extensors) impaired a pointing task by increasing the movement
101 duration to guarantee task success, i.e., precision. From an
102 ecological aspect, several studies have previously investigated
103 the impact of muscle fatigue on specific sport motor skills by
104 measuring simultaneously these parameters during racket sports.
105 These studies demonstrated that precision is largely affected in
106 fatigued condition in tennis¹¹ and table tennis¹⁵ whereas ball
107 speed is less deteriorated. However, this result was not
108 systematic¹³. To the best of our knowledge, no study has

109 attempted to evaluate the impact of muscle fatigue on sport
110 motor skills during a specific badminton task.

111 This study aimed therefore to evaluate the impact of muscle
112 fatigue on badminton-specific technical performance. To do that,
113 we have first developed a field test to evaluate the reliability for
114 both precision and shuttlecock speed during a smash stroke,
115 which is classically considered as the most powerful stroke,
116 generally used for winning the rally¹⁶ (Study 1). Thereafter, this
117 test was performed before and after a fatiguing protocol (Study
118 2) to measure in what extent fatigue could impair the speed
119 and/or the accuracy of the shuttlecock during a specific
120 badminton stroke.

121

122 **METHODS**

123 *Participants*

124 Fifty-five participants (mean \pm SD age: 22.7 ± 5.7 yr;
125 height: 179.9 ± 6.9 cm; mass: 71.9 ± 6.2 kg) volunteered to
126 participate in this study. All participants or legal representatives
127 for minors gave their written consent after being informed about
128 the procedures of the protocols, which were approved by local
129 ethics committee of Nantes, in accordance with the Declaration
130 of Helsinki. Among these players, thirty-eight (males only, mean
131 \pm SD age: 25.3 ± 5.0 yr; height: 181.2 ± 5.5 cm; mass: 74.1 ± 4.8
132 kg) participated in Study 1, i.e., reproducibility of the specific
133 test, and seventeen (M=11, F=6, 17.0 ± 0.8 yr, 177.0 ± 8.8 cm,
134 67.1 ± 6.4 kg) participated in Study 2, i.e., effects of muscle
135 fatigue on badminton-specific technical performance.

136 *Study design*

137 **Study 1**

138 Players were divided into four groups according to their single
139 ranking in the French Federation of Badminton (FFBad) and
140 their training volume (Table 1). In the high trained group (HT,
141 n=9), all players were high-trained (4.9 ± 1.3 times per week)
142 and participated in national competitions. In the moderate
143 trained group (MT, n=10), players were moderate to well-trained
144 (3.1 ± 1.0 times per week) and participated in a regional
145 championship. In the low trained group (LT, n=9), players were
146 less trained (2.0 ± 0.7 times per week) and participated in a local
147 championship. The untrained group (UT, n=10) was composed
148 by sports-science-students, without experience in badminton and
149 not ranked by the FFBad.

150 After a 15-min standardized warm-up and once familiarized (10
151 trials) with the procedures, all the participants performed one

152 session which consisted of performing the specific test (see
153 specific test) twice (intra-session reliability), with a 10-min
154 resting period in between. Thirty-three participants, among the
155 38 participants initially recruited, participated in a second
156 session to assess the inter-session reliability. A minimum of 7
157 days interval was defined between both sessions.

158 Study 2

159 All participants (n=17) were recruited from French National
160 badminton training centers and were well-trained (15.5 ± 1.8
161 h.wk⁻¹), regularly participated in national competitions in the
162 French championship, and none of them had any known
163 muscle/tendon injury for at least one year. One session (duration:
164 ~ 45 min) was performed to assess the effects of muscle fatigue
165 on badminton-specific technical performance. All sessions took
166 place in a homologated specific facility comprising two courts.
167 All participants were familiarized with all procedures at the
168 beginning of the session. Before and immediately after (~30 s)
169 completion of the fatigue protocol (see below for further details)
170 participants performed the specific badminton test (see specific
171 test) to measure the quality (precision and speed of the
172 shuttlecock) of the smash. To control for the effect of the
173 fatiguing protocol, both subjective (perception of effort) and
174 objective (maximal height during a countermovement jump
175 [CMJ]) measurements of fatigue were assessed.

176 We quantified badminton-specific technical performance by
177 measuring stroke parameters during the specific test previously
178 described (Study 1). The test took place in a second court, close
179 to the one used during the fatigue protocol. To take into account
180 the ecological aspects of badminton smash¹⁷, male players were
181 asked to jump when performed the stroke while this rule was not
182 mandatory for the female players.

183 Specific test

184 The test consisted in 20 forehand overhead smash, which is
185 considered as a typical offensive stroke. They were asked to hit,
186 alternatively, two targets placed on the court (Fig 1A). The 2
187 rectangular targets (212 cm length/40 cm width) were positioned
188 on the sides and were divided into 2 areas (212 cm length/20 cm
189 width; Fig 1A). The players were instructed to hit the shuttlecock
190 (Aerosensa 50, Yonex®, Tokyo, Japan) for winning the rally as
191 they do during an official game. Ten trials were evaluated for
192 each target. The shuttlecock was sent by a robot (BKL,
193 Badenko®, Pampelonne, France) to ensure protocol
194 standardization and repeatability for shuttlecock speed,
195 trajectory and placement. For each trial, the robot sent the
196 shuttlecock to the center of the court, placing it 75-80 cm away
197 from the baseline (Fig 1A). The shuttlecock was delivered by the

198 robot every 3 s with a rising trajectory. New shuttlecocks were
199 used for each session and were replaced when they were
200 damaged.

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

205 **Muscle fatigue**

206 To induce muscle fatigue (study 2), participants completed 10
207 series of two specific movements frequently used by the
208 badminton players, i.e., CMJ¹⁷ and lunges^{9,17,18}. Each series
209 consisted of ten CMJ performed every 3 s. CMJ were realized
210 hands akimbo, and subjects were asked to perform each trial
211 maximally. Once the CMJ performed, subjects kept their own
212 racket and had to realize 8 lunges with no rest between the two
213 exercises. During the lunges task, participants were asked to
214 touch alternatively the right and the left parts of the net with their
215 racket (1-m width). Between two lunges, participants moved 1-
216 m behind the short service line before continuing the exercise
217 (Fig 1B). Once the exercise completed, subjects came back
218 walking (10-s) to the baseline, rated their perceived exertion, and
219 started a new series, until 10 series were performed. During the
220 last series, subjects only performed 10 CMJ, without execution
221 of lunges to better assess the fatigue induced by our protocol,
222 since CMJ represents the objective measure of fatigue used in
223 this study. The instruction was given to the players to directly
224 move on the badminton test after the last series of CMJ. This
225 protocol was chosen to induce a level of fatigue consistent with
226 the one observed during a real badminton game. We assume that
227 it represented a good compromise, taking into account the
228 duration of the protocol (~7 min), the number of lunges and
229 jumps performed⁹. To maintain motivation, subjects were
230 strongly encouraged during the entire protocol.

231

232 *Data processing*

233 **Shuttlecock speed**

234 For each smash, the speed of the shuttlecock hit by the player
235 was measured with a radar (Stalker ATS ii, Stalker Radar®,
236 Plano, Texas, USA) at a frequency of 50 Hz and an accuracy of
237 ± 0.041 m.s⁻¹. The radar was located 3 m behind the player, at a
238 height of 2.50 m⁴. To ensure recording of the speed data, an
239 experimenter manually pointed the radar towards the area
240 targeted by the player. All data were recorded on a personal
241 laptop (software: Stalker ATS 5.0, Plano, Texas, USA). The
242 shuttlecock speed for each of the 20 smashes was measured. The

243 mean speed was then calculated by averaging the 20 speed
244 values.

245 **Precision**

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

258 *Perception of effort (RPE)*. In study 2, perception of effort,
259 defined as “the conscious sensation of how hard, heavy, and
260 strenuous the physical task is”²⁰ was measured throughout the
261 fatigue protocol. Participants were asked to rate the effort related
262 to the physical task just performed by using the 6-20 Borg
263 Scale²¹ after the first nine series.

264 *CMJ*. In study 2, optojump photoelectric cells (Microgate,
265 Bolzano, Italy) were used to precisely measure the jump
266 height²². Fatigue was assessed by calculating the average of the
267 height of the 10 CMJ performed from each series. We also
268 compared CMJ performance between the average of the first
269 three CMJs of the first series (trials 1-3) and the last three CMJs
270 of the last series (trials 98-100). All data were recorded on a
271 personal laptop with the appropriate software (Optojump
272 software, version 3.01.0001) for further treatment.

273

274 *Statistical analysis*

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

281 **Study 1**

282 Speed and precision were compared across the four populations
283 by using a one-way analysis of variance (ANOVA) (4 between-
284 subjects factors) for the first series of the first day. Correlation
285 analyses (Bravais-Pearson) were performed to determine

286 whether speed, precision, or performance index were correlated
287 to the skill level (i.e., FFBad ranking). For each group, standard
288 error of measurements (SEM), intraclass correlation coefficients
289 (ICC) and coefficient of variation (CV) were calculated for both
290 intra-day and inter-day²³. Since we used a set time between
291 sessions, the ICC (3, 1) was chosen from Shrout and Fleiss²⁴.
292 Inter-day reliability was assessed by using the first series of day
293 1 vs. the first series of day 2.

294 Study 2

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

300

301 In both studies, the level of significance was set at $P < 0.05$ and
302 post-hoc analyses were performed when appropriated using
303 HSD Tukey test for multiple comparisons. For the main effects
304 of the ANOVAs, partial eta square (η_p^2) are reported, with
305 moderate and large effects considered for $\eta_p^2 \geq 0.07$ and ≥ 0.14 ,
306 respectively²⁵. For the follow up tests, Cohen's effect sizes d are
307 reported, with small, moderate and large effects considered for d
308 ≥ 0.2 , ≥ 0.5 and ≥ 0.8 , respectively²⁵.

309

310 RESULTS

311 Study 1

312 *Effect of expertise on performance factors*

313 *Shuttlecock speed*

314 Our results showed a significant effect of expertise ($\eta_p^2 = 0.954$;
315 $P < 0.001$). Shuttlecock speed was higher for HT (158.1 ± 5.5
316 km.h^{-1}) compared to MT, LT and UT ($136.4 \pm 4.0 \text{ km.h}^{-1}$, 121.0
317 $\pm 4.2 \text{ km.h}^{-1}$ and $101.7 \pm 5.3 \text{ km.h}^{-1}$, d ranged from 4.51 to 10.44,
318 respectively; $P < 0.001$), for MT compared to LT and UT (d
319 ranged from 3.79 to 7.42, respectively, $P < 0.001$), and LT
320 compared to UT ($d = 4.04$, $P < 0.001$). In addition, a significant
321 correlation was observed between the speed of the shuttlecock
322 and the ranking of the player ($r = -0.81$; $P < 0.001$; $n = 28$, UT
323 excluded).

324 *Precision*

325 A significant main effect was observed for precision ($\eta_p^2=0.849$;
326 $P<0.001$), showing that the score of precision (/60) was higher
327 for HT (33.1 ± 2.5) compared to MT, LT and UT (26.1 ± 2.4 ,
328 21.3 ± 1.7 and 18.4 ± 3.0 , d ranged from 2.86 to 5.52,
329 respectively; $P<0.001$), for MT compared to LT and UT (d
330 ranged from 2.26 to 2.85, respectively; $P=0.001$ and $P<0.001$,
331 respectively). A significant correlation was also found between
332 precision and ranking of the players ($r=-0.78$; $P<0.001$; $n=28$,
333 UT excluded).

334 *Intra- and inter-session reliability*

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

344 Study 2

345 *Effects of the fatigue protocol*

346 **Perception of effort.**

347 There was a significant effect of time on the perceived exertion
348 ($P<0.001$, $\eta_p^2=0.852$). RPE progressively increased throughout
349 the fatigue protocol (from 12.0 ± 1.7 after the first series to 18.8
350 ± 0.8 after the 9th series).

351 **CMJ height.**

352 There was a main effect of time on the height performed during
353 the CMJ ($-10.1 \pm 6.8\%$, $P<0.001$, $\eta_p^2=0.468$, **Fig 2**). The best
354 performance was measured after the first series (32.4 ± 4.6 cm)
355 while the weakest performance was measured after the last series
356 (29.0 ± 4.0 cm). The greatest difference was observed between
357 the first three CMJs of the first series (32.9 ± 4.6 cm) and the last
358 three CMJs of the last series (27.4 ± 4.5 cm), i.e. $-16.9 \pm 9.8\%$
359 ($d_z=1.692$, **Fig 2**).

360 *Effects of muscle fatigue on badminton performance*

361 **Shuttlecock speed.**

362 There was a significant effect of time for the shuttlecock speed
363 ($P<0.001$, $\eta_p^2=0.671$). This parameter decreased about $3.3 \pm$
364 2.4% in the fatigued state, from 151.2 ± 4.6 km.h⁻¹ to $146.2 \pm$
365 3.9 km.h⁻¹ (**Fig 3A**).

366 **Total score.**

367 There was a significant effect of time for the total score
368 ($P=0.001$, $\eta_p^2=0.473$). This parameter decreased about $10.3 \pm$
369 10.3% in the fatigued state, from 27.4 ± 5.9 to 24.4 ± 4.7 (Fig
370 3B).

371 **Distribution.**

372 There was a main effect of time on the number of faults
373 committed by the players (from $29.7 \pm 13.3\%$ to $37.9 \pm 11.6\%$,
374 $P=0.006$, $\eta_p^2=0.378$, $d_z=0.756$). There was no main effect of time
375 on consistency (from $19.7 \pm 13.0\%$ to 20.0 ± 10.2 , $P=0.918$,
376 $\eta_p^2=0.0006$, $d_z=0.026$) while a clear trend was observed for
377 accuracy, with small to moderate effect size (from $23.5 \pm 8.8\%$
378 to $19.7 \pm 6.0\%$, $P=0.066$, $\eta_p^2=0.195$, $d_z=0.478$, Fig 3C).

379 **DISCUSSION**

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

384 **Specific test**

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

403 *Markers of fatigue*

404 **Psychological marker.** The perceived exertion regularly
405 increased throughout the fatigue protocol, showing that the
406 players were close to exhaustion before performing the second
407 badminton test. Although it should be kept in mind that RPE
408 measured during official junior games is less than that induced

409 in the current study (~14.5 vs 18.8)¹⁹, it is plausible that after a
410 particularly challenging rally, the perceived exertion is
411 significantly greater than that measured at the end of the game.
412 Thus, Abian et al.²⁸ showed that in the modern badminton, the
413 rally duration tends to increase, as well as the recovery between
414 two rallies, reflecting a more demanding physical condition.
415 Therefore, although the perceived exertion measured at the end
416 of the fatigue protocol was very high, we assume that such a
417 fatigue may occasionally exist during badminton game.

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

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

429 *Fatigue impairs specific badminton skill*

430 In the current study, we observed that fatigue phenomenon,
431 assessed by both subjective (increased RPE) and functional
432 (decreased CMJ performance) parameters, induced a moderate
433 but significant decrease of the speed of the shuttlecock during a
434 smash stroke ($-3.3 \pm 2.4\%$). Such a result has previously been
435 reported in tennis¹³ while Le Mansec et al.¹⁵ did not find any
436 decrease of this parameter after both upper and lower limb
437 fatigue during table tennis stroke. Yet, by reporting significant
438 differences in shuttlecock speed during the smash stroke
439 depending on the level of the players, previous⁴ and current
440 (Study 1) studies demonstrated that this parameter was very
441 discriminant to perform at a high level during a badminton game.
442 Thus, despite their fatigue level, the players tried to maintain,
443 consciously or unconsciously, a high shuttlecock speed during
444 the second specific test.

445 We also found that the precision was significantly decreased
446 during the second badminton specific test, i.e., after the fatigue
447 protocol. This decrease in precision was mainly due to an
448 increase in the number of faults and, to a lesser extent, to a
449 decrease in accuracy. Thus, although Missenard et al.¹⁴ showed
450 that during a pointing task, fatigued participants decreased the
451 speed of their movement in order to maintain their task success,
452 the present study gave evidence that, during a specific badminton
453 motor skill, players have given priority to the speed of the
454 shuttlecock, even if this led to commit more faults or reach the

455 target less often. This result has already been observed in racket
456 sports such as tennis¹¹ and table tennis¹⁵.

457 *How fatigue impairs stroke performance during*
458 *badminton smash?*

459 Since the design of the current study was mainly descriptive, we
460 did not have access to the underlying mechanisms, which were
461 able to explain the results observed. However, based on previous
462 studies, we can advance some hypotheses. Indeed, Sakurai and
463 Ohtsuki⁵ showed that high skilled badminton players had
464 consistent motor program, i.e., reliability of the muscle activity
465 pattern, when they performed badminton smash. This ability to
466 perform consistently results in a lower unforced errors⁵, which
467 has a great influence in winning or losing the game³⁰. However,
468 the coordination may be affected and a shift in motor control can
469 be observed when fatigue is experienced, leading to conflicting
470 results^{11,31,32}. For instance, despite changes in technical factors
471 induced by muscle fatigue, speed and accuracy were unchanged
472 during a specific water polo motor skill³². As regards table
473 tennis, Aune et al.³¹ suggested that, when fatigued, high skilled
474 players adjusted the motor coordination strategy to maintain
475 accuracy, as explained by Missenard et al.¹⁴. Conversely, Rota
476 et al.¹¹ showed that fatigue in upper limb muscles induced a
477 decrease in forehand stroke accuracy associated with changes in
478 muscle activation level, while the speed of the ball was
479 maintained. Even if muscle activation was not measured in the
480 current study, it might be speculated that changes in the level of
481 activation of fatigued muscles could partly explain our results.
482 However, further studies are required to better understand the
483 biomechanical origins (e.g. muscular coordination pattern) of the
484 decrease in smash stroke performance observed herein.

485 It is classically accepted that the temporal structure, the
486 notational analysis or the physiological characteristics may vary
487 depending on the gender, suggesting a higher demand during the
488 games for males¹⁷. This aspect is reinforced by the study of
489 Fernandez-Fernandez et al.¹⁹, who showed that the activity
490 pattern of the match is different between young males and young
491 females players (16 yr), but induced only slight different
492 physiological responses, i.e. same heart rate, blood lactate
493 response, RPE. Consequently, it could be possible that the
494 protocol used in the present study to induce fatigue may affect
495 female players in a different manner than male players and
496 change our results. However, no gender differences appeared for
497 the markers of fatigue (RPE: 18.9 ± 0.7 vs 18.6 ± 1.0 ; CMJ: -
498 $10.4 \pm 4.6\%$ vs $-9.4 \pm 10.3\%$ for males and females,
499 respectively). Similarly, no gender difference was observed for
500 the decrement in speed of the shuttlecock ($-3.4 \pm 2.0\%$ vs $-3.0 \pm$
501 3.1%). Only the decrease of the precision was different, i.e.
502 greater for males ($-13.2 \pm 8.0\%$), when compared to females (-

503 5.1 ± 12.7%), possibly due to the fact that females do not jump
504 for smash. Taken as a whole, gender seems to have a little
505 influence on our results.

506 *Practical applications*

507 The results of the current study, i.e., decrease in both speed
508 (moderate) and precision (large effect) of the shuttlecock
509 following a fatiguing protocol, are relevant for coaches and
510 physical trainers, since the number of unforced errors is an
511 important factor to win the game³⁰ and the speed of the missile
512 is also determinant to perform at high level⁴. Thus, coaches,
513 physical and/or mental trainers should accustom badminton
514 players to experience fatigue during training and to propose
515 relevant training programs in order to minimize the magnitude
516 of the deleterious effect of fatigue during the game.

517

518 **CONCLUSION**

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

525

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534

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- 637

638 **Table caption**

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

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

641

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

643 **Table 2.** Intra- and inter-reliability for shuttlecock speed and precision for high trained (HT), moderate trained (MT), low trained (LT) and untrained
644 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
645 the second session. ICC: intraclass correlation coefficient; CV: coefficient of variation; SEM: standard error of measurement. Values are mean \pm
646 SD.

647 **Figure captions**

648

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

655

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

660

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