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Badminton preferentially decreases explosive over maximal voluntary torque in both the plantar flexors and extensors

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We assessed changes in maximal and explosive plantar flexion (PF) and dorsi flexion (DF) torque, and thus the maximal and explosive DF/PF ratio, in response to successive badminton matches (2 × 35, 15 minutes of rest) in 16 juniors (10 males, 6 females) International-level badminton players before (Pre), immediately after the first (Post-1) and second (Post-2) match as well as after resting for 12 hours. For both PF and DF, maximal voluntary torque decreased from Pre to Post-2 (~7%-9%; $P < 0.05$). Compared with Pre, PF explosive voluntary torque decreased by ~4%-13% at Post-1 ($P < 0.05$), with further reductions ranging from −15% to −25% within the 0-100 ms epoch after contraction ($P < 0.001$) at Post-2. Decrements of similar magnitude in DF explosive voluntary torque occurred at Post-1 (ranging −7% to −27%) and Post-2 (ranging −3% to −28%) relative to Pre ($P < 0.05$). All neuromuscular parameters were fully recovered after 12 hours of rest. Explosive DF/PF ratios during the very initial phase of contraction (up to 50 ms from onset) were lower compared with the maximal DF/PF ratio, with no effect of time (all $P < 0.05$). In badminton, explosive torque indices should be included to more accurately reflect acute fatigue induced by successive badminton matches.

KEYWORDS
ankle joint, antagonist/agonist strength ratio, badminton, explosive strength, maximal strength

1 | INTRODUCTION

Success in badminton requires the ability to produce repetitive explosive actions during on-court movements (ie, quick lunge and return to the start or move off in another direction), characterized by high levels of muscle force or torque production within the initial phase of contraction.[1] It is therefore not surprising that badminton players possess greater quadriceps and hamstring maximal and explosive muscle strength than age-matched individuals who are recreationally physically active.[2]

Muscle strength evaluation in badminton players (as in other racket sports) is mainly concerned with maximal voluntary torque (MVT).[3] This approach, however, is questionable since MVT often requires more than 300 ms to develop under isometric conditions.[4] In badminton, fatigue-induced changes in the ability to develop force or torque rapidly/explosively (ie, contractile rate of torque development or RTD) may be larger than maximum muscle strength per se. Hence, end-exercise reductions in explosive voluntary torque (EVT) of the knee extensors exceed (−15% to −25%) MVT values (−10% to −12%) following a handball match[5] and repeated cycling sprint exercise.[6]

In the fatigue-related literature, little attention has been given to study changes in EVT of the plantar flexors (PF), while virtually no data are available for dorsi flexors (DF). We previously examined the acute and delayed PF neuromuscular consequences of a one-off football[7] or tennis[8] match in semi-professional players. In football, acute match-related changes in EVT were seen in the very early phase (0-30 ms epoch) of the contraction, with no change at any other time interval.[7] In tennis, EVT remained unchanged in response to prolonged (~2 hours) tennis playing.[8]

In badminton, the actions of the ankle joint muscles are important both in controlling ankle joint stability during side-cutting or by decreasing the strain imposed on the Achilles tendons during high force ground contact/landing situations.[9] Under fatigue, any reduction in MVT and/or EVT in both PF and DF would be expected to negatively impact explosive-type actions typically seen during on-court movements. Furthermore, little is known about the recovery of neuromuscular function integrity in ankle joint muscles for either maximal or explosive performance in the hours after match completion. This information is important to inform recovery practice since competitive scenarios in badminton often impose that players participate in multiple matches in a single day.

Imbalance between antagonist and agonist muscles has traditionally been assessed by “conventional” concentric antagonist/agonist ratio (eg, hamstring/quadriceps ratio) derived from peak torque values during an MVC.[10] Considering the short-time history of non-contact injury in badminton (<100 ms after foot contact),[11] calculating antagonist/agonist ratios from MVT values is questionable. Alternatively, the explosive ratio of antagonist vs agonist torque production assessed over shorter time frames (< 200 ms) has been proposed as a more relevant measure of joint stabilization.[12] While previous fatigue studies have almost exclusively investigated the explosive hamstring/quadriceps ratio, for instance in football players,[13,14] there are no published reference values for the ankle joint in badminton.

Our aim was to assess changes in plantar flexion (PF) and dorsi flexion (DF) MVT and EVT, and thus the maximal and explosive DF/PF ratios, in response to two successive simulated badminton matches on the same day. We hypothesized that successive badminton matches would induce earlier and larger impairments in EVT in reference to MVT, yet of similar magnitude for both PF and DF and therefore preserved maximal and explosive DF/PF ratios.

2 | METHODS

2.1 | Participants

Sixteen well-trained, junior badminton players (10 males, 6 females; age 16.2 ± 0.8 years, body mass 63.5 ± 6.6 kg, height 173.2 ± 6.3 cm) with International experience participated in the study. This research project was approved by the local research ethics committee and conformed to the recommendations of the *Declaration of Helsinki* for use of human subjects. The players and their parents were provided with the procedures and risks associated with participation in the study. Written informed consent was obtained from the players and their parents (for minors).

2.2 | Study design

All measurements were taken from players during the days preceding an invitational singles badminton tournament held in a local badminton club (Oviedo, Spain). Upon arrival (between 5 and 6 PM) to the testing/competition venue (well-ventilated at a constant temperature of ~18°C and 40% relative humidity), participants were first thoroughly familiarized with the testing procedures and neuromuscular function assessment protocol until they felt accustomed with the equipment (ie, coefficient of variation in three successive MVC and explosive contractions [200 ms after contraction onset] trials lower than 3% and 5%, respectively). This was followed after ~10 minutes of rest by the baseline (Pre) neuromuscular function assessment (duration < 3 minutes; see below), while similar tests were performed 3-5 minutes after a first and a second 35-minutes badminton match (Post-1 and Post-2, respectively) as well as after 12 hours of rest (+12 hours) the following morning between 9 and 10 AM. Quick (<30 seconds) setup (ie, subject positioning, straps attachment) was possible thanks to the help of two experienced staff, while the dynamometric pedal was located in a quiet room beside the badminton playing area.

2.3 | Simulated badminton matches

After an individual warm-up of about 10 minutes (eg, jump rope, mobility exercises, and playing several points), participants played two simulated badminton matches of 35 minutes each, with 15 minutes rest in between (total of 85 minutes), to reflect actual competition scenarios.[3,15] Opponents were matched for performance ability (similar national rankings) and gender. The matches were friendly games following Badminton World Federation rules but with a competitive setup and a (minor) reward to the winning player to secure maximal “competitive” effort by all participants. The players were supplied with pure water at the sidelines with ad libitum intake during the games, but no artificial breaks were provided.

2.4 | Neuromuscular function

The neuromuscular assessment protocol was performed twice: once to evaluate the PF and once to evaluate the DF. Neuromuscular test sessions began by the completion of three successful MVCs, all brief (~5 seconds) and separated by ≥30 seconds of rest. Participants were instructed to increase torque production over a 1-second period, hold it for 3-4 seconds and then relax before completing the next

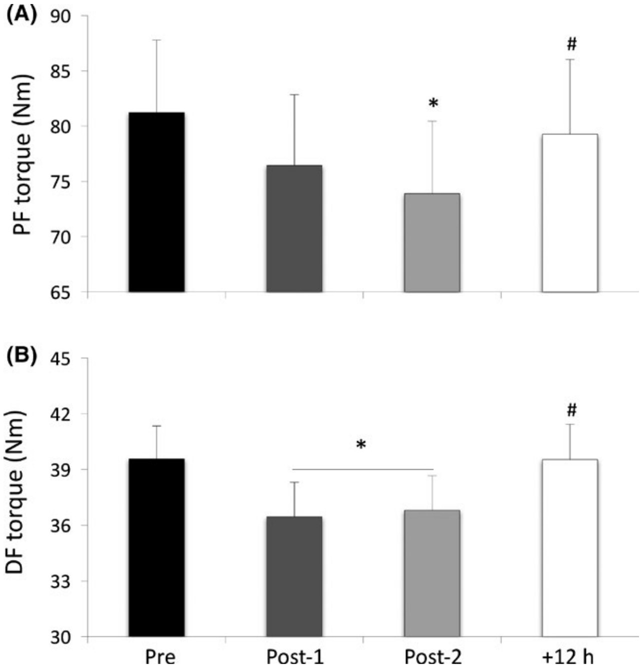

FIGURE 1 Maximal isometric voluntary contraction torque in plantar flexors (A) and dorsi flexors (B) before (Pre), immediately after the first (Post-1) and second (Post-2) badminton match as well as after resting for 12 h (+12 h). *Significantly different from Pre. #Significantly different from previous time interval

contraction. Thereafter, participants were instructed to perform three "explosive" contractions (separated by ≥ 20 seconds) where participants were carefully instructed to contract "as fast as possible" for ~1 second from a fully relaxed state, in an attempt to achieve at least 90% of their MVC torque. Participants were asked to avoid any countermovement before torque onset; that is, they were reminded not to dorsiflex the foot immediately prior to plantar flexion (and vice versa). Contractions that had any discernible countermovement or pre-tension (ie, change of baseline torque of >0.5 Nm during the 100 ms before contraction onset)[7,8] were discarded and another attempt was made. To provide biofeedback on whether a countermovement had occurred, the resting torque level was displayed on a sensitive scale. Pre- and +12 hours post-match assessments were preceded by a standardized warm-up consisting of 10 isometric PF and DF contractions (alternating 4 seconds of contraction and 6 seconds of rest). Contraction intensity was progressively self-adjusted by the subject to attain peak torque in the last three efforts.

2.5 | Torque measurements

Isometric PF and DF torque of the right foot was measured using a dynamometric pedal (Captels, St Mathieu de Treviers, France). The subject's seating position was standardized with pelvis, knee, and ankle angulations of 90°, the foot securely strapped on the pedal by three straps, and a motionless head. During all contractions, the torque signals were sampled at 2000 Hz by commercially available hardware and software (MP36 and BSL Pro Version 4.1, Biopac Systems Inc., Santa Barbara, USA).

2.6 | Data analysis

The MVC torque was defined as the maximum value recorded for 1 second when the torque had reached a plateau. The contractile RTD (expressed as Nm s^{-1}) was derived from the "explosive" contractions, as the average slope of the initial time phase of the torque-time curve at 0-30, 0-50, 0-100, 0-150, and 0-200 ms, relative to the onset of contraction using a custom written program (Spike 2 Software, Cambridge Electronic Design, Cambridge, UK). The onset of muscle contraction was defined as the time point at which the torque curve exceeded the baseline by >1.5 Nm, corresponding to ~2.5% of MVC torque values.[7,8,16] In addition, raw RTD data were normalized relative to MVC torque (%MVC). For both MVT and EVT, the average of three trials was used for further analysis.

Finally, DF torque was expressed relative to PF torque to produce maximal and explosive DF/PF ratios. Specifically, explosive DF/PF ratios were calculated by dividing explosive DF torque with explosive PF torque values in the examined time period (ie, 0-30, 0-50, 0-100, 0-150, and 0-200 ms, for example, explosive DF torque for the period 0-100 ms divided by PF torque for the same time interval, etc).[12]

2.7 | Statistical analysis

Values are expressed as means ± SD. Two-way repeated measures analysis of variances (Time [Pre, Post-1, Post-2, and +12 hours] × Analysis epoch [0-30, 0-50, 0-100, 0-150, and 0-200 ms]) for absolute and relative changes for each muscle group (PF and DF) separately. For maximal and explosive DF/PF ratios, the effect of time was determined by a single-factor ANOVA for repeated measures across each analysis epoch. Outcome variables were tested using Mauchly's procedure for sphericity. Whenever the data violated the assumption of sphericity, P values and adjusted degrees of freedom based on Greenhouse-Geisser correction were reported instead. Where significant effects were established, pairwise differences were identified using the Bonferroni post-hoc analysis procedure adjusted for multiple comparisons. For each ANOVA, partial eta-squared was calculated as measures of effect size. Values of 0.01, 0.06, and above 0.14 were considered as small, medium, and large, respectively. All statistical calculations were performed using PASW software V.24.0 (SPSS, Chicago, Illinois, USA). The significance level was set at $P < 0.05$.

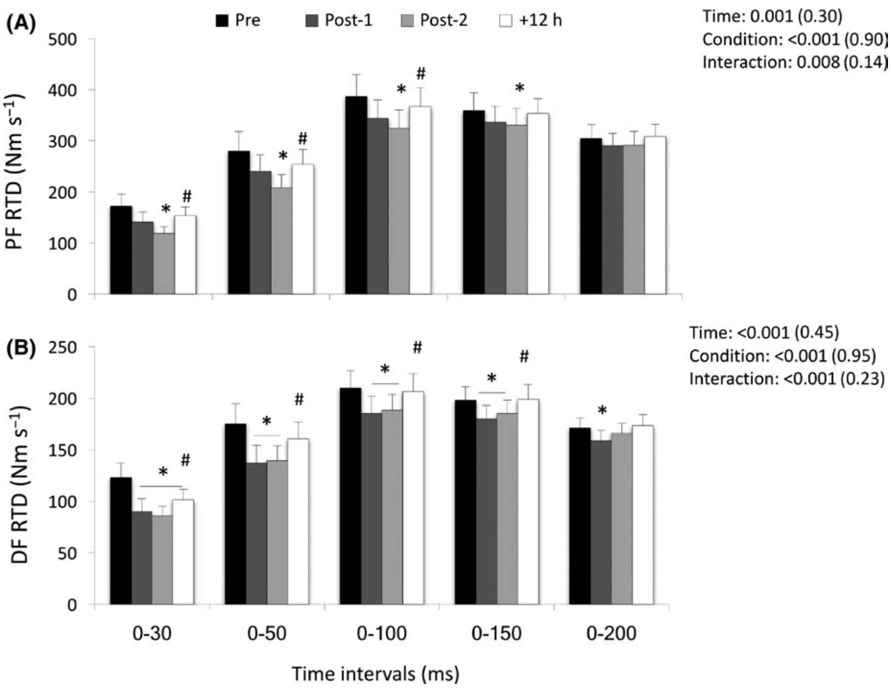

FIGURE 2 Rate of torque development during explosive isometric plantar flexions (A) and dorsi flexions (B) obtained at 0-30, 0-50, 0-100, 0-150, and 0-200 ms before (Pre), immediately after the first (Post-1) and second (Post-2) badminton match as well as after resting for 12 h (+12 h). *Significantly different from Pre. #Significantly different from previous time interval

3 | RESULTS

3.1 | Maximal voluntary torque of the PF and DF

For both PF and DF, maximal torque decreased from Pre to Post-1 (−6.1 ± 10.0% and −8.2 ± 6.1%; $P = 0.117$ and $P < 0.001$, respectively) and Post-2 (−9.5 ± 9.8% and −7.2 ± 5.4%; $P < 0.001$ and $P = 0.013$, respectively) but returned near baseline after 12 hours (Figure 1).

3.2 | Explosive voluntary torque of the PF and DF

Compared with Pre, PF RTD decreased at Post-1 (−13.3 ± 30.0%, −10.4 ± 21.1%, −9.0 ± 11.3%, −5.0 ± 10.2%, and −3.6 ± 11.5% at 0-30, 0-50, 0-100, 0-150, and 0-200 ms, respectively; all $P < 0.05$) and was further reduced, during early time intervals only (−25.2 ± 22.9%, −21.4 ± 20.1%, and −14.9 ± 10.5% at 0-30, 0-50, and 0-100 ms, respectively; all $P < 0.001$), at Post-2 (Figure 2). A similar reduction in DF RTD occurred at Post-1 and Post-2 (ranging −27.3 ± 16.7% to −7.5 ± 6.9% and −27.6 ± 14.4% to −3.0 ± 7.9% within the 0-30 to 0-200 ms epoch after contraction onset, respectively; all $P < 0.05$) relative to prematch. Reductions in RTD for both PF and DF were fully restored after only 12 hours of rest.

Normalized PF RTD decreased at Post-2 during early time intervals only (−16.0 ± 29.5%, −11.7 ± 26.9%, and −5.1 ± 14.9% at 0-30, 0-50, and 0-100 ms, respectively; all $P < 0.05$) relative to Pre (Figure 3). Compared with Pre, normalized DF RTD was reduced at Post-1, Post-2, and +12 hours (−21.5 ± 18.7%, −21.5 ± 17.2%, and −13.5 ± 18.4%, respectively; all $P < 0.05$) within the 0-30 ms time interval, while was also lower in the 50 ms epoch at Post-1 (−15.5 ± 15.4%; $P < 0.05$) and Post-2 (−12.4 ± 13.1%; $P < 0.05$).

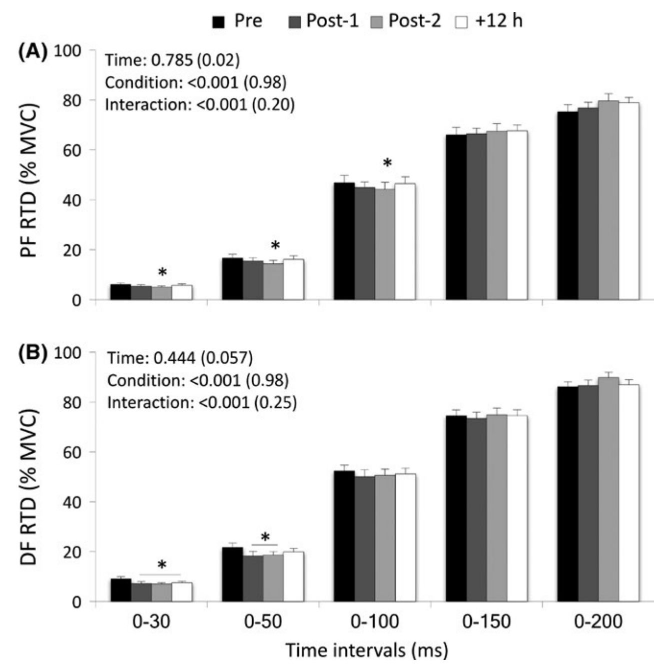

FIGURE 3 Normalized rate of torque development during explosive isometric plantar flexions (A) and dorsi flexions (B) obtained at 0-30, 0-50, 0-100, 0-150, and 0-200 ms before (Pre), immediately after the first (Post-1) and second (Post-2) badminton match as well as after resting for 12 h (+12 h). *Significantly different from Pre.

3.3 | Maximal and explosive DF/PF ratios

There was no significant effect of time on maximal DF/PF ratios ($P = 0.502$; $\eta = 0.050$). Whereas there was no significant time ($P = 0.507$; $\eta = 0.05$) or analysis epoch × time ($P = 0.706$; $\eta = 0.05$) interaction, explosive DF/PF ratios differed according to the analysis epochs considered ($P < 0.001$; $\eta = 0.39$) (Figure 4). Post-hoc tests showed higher values ($P < 0.001$) for explosive DF/PF torque ratios during the very initial phase of contraction (up to 50 ms from onset) compared with the maximal DF/PF ratio.

3.4 | Correlations

In general, moderate-to-strong relationships were observed between the maximal DF/PF ratio and explosive DF/PF ratios, with progressively stronger correlation coefficients between these parameters as the time from the onset of contraction lengthens; that is, in the epochs 0-30 ($r = 0.38$, $P = 0.002$), 0-50 ($r = 0.43$, $P < 0.001$), 0-100 ($r = 0.64$, $P < 0.001$), 0-150 ($r = 0.74$, $P < 0.001$), and 0-200 ms ($r = 0.81$, $P < 0.001$). An example of correlation between the maximal DF/PF ratio and the explosive DF/PF ratio for the period 0-200 ms is given in Figure 5, where the explained variance was ~74%.

4 | DISCUSSION

Our study is the first to profile the neuromuscular fatigue response to two successive 35-minutes badminton matches with 15 minutes of rest in between (ie, similar to a competition scenario), with special reference to explosive performance in the ankle joint. In agreement with our hypothesis, torque losses for both the PF and DF after the first and second simulated game were twice larger during explosive compared with maximal efforts, recovering fully within 12 hours. Our results also indicate that decrements in EVT with fatigue were mainly visible during the early phase of muscle contraction. Finally, muscle balance around the ankle joint (maximal and explosive DF/PF ratios) was preserved.

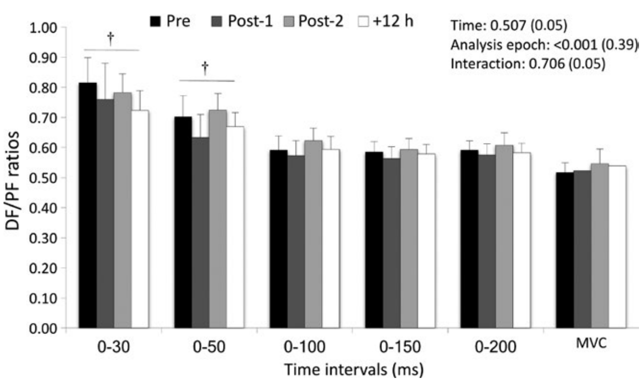

FIGURE 4 Maximal dorsi flexion/plantar flexion (DF/PF) ratio and explosive DF/PF ratios obtained at 0-30, 0-50, 0-100, 0-150, and 0-200 ms before (Pre), immediately after the first (Post-1) and second (Post-2) badminton match as well as after resting for 12 h (+12 h). †Significantly different from MVC

4.1 | Maximal voluntary strength

Decrements in MVT from Pre to Post-1 were of similar magnitude (−6%-8%) for PF and DF, with little additional decrement (−7%-9%) recorded at Post-2. Contrastingly, we previously observed that PF voluntary torque assessed every 30 minutes during a 3-hours tennis match followed a biphasic pattern with a slight but significant decrease in PF MVC torque after 90 minutes (~−4%) and a further marked decrease at match end (~−15%).[17] While no data exists for the DF, our observations in PF also contrast with those of previous studies showing that pre- to post-match reductions in PF MVC torque in well-trained soccer[18] or tennis[8] players are rather modest and not significant. Nonetheless, a direct comparison among studies must be made with caution, as the nature of the testing conducted to assess leg fatigue, and the nature and characteristics of the simulated game, all differ considerably between studies. Our findings suggest that the badminton match produced significant muscle fatigue levels in both the PF or DF and that these neuromuscular alterations develop quite rapidly as most of the adjustments were already present after playing the first of the two 35-minutes matches. Another important observation was that MVT values for either ankle muscle groups recovered quickly, only after a night of rest (12 hours) with

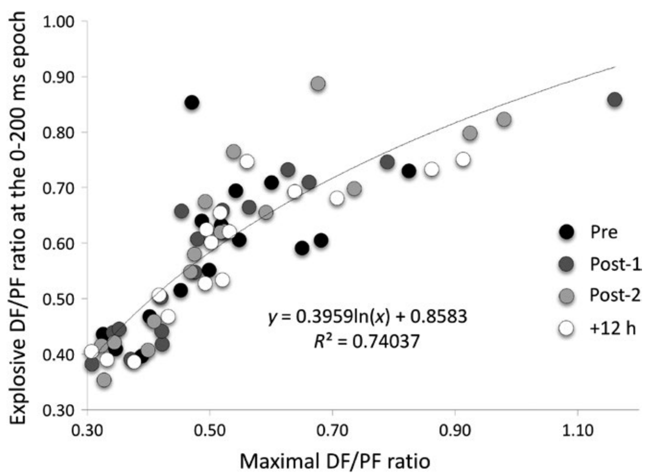

FIGURE 5 Relationship between dorsi flexion/plantar flexion (DF/PF) torque ratios obtained at 0-200 ms and during maximal voluntary contractions (MVC). Data obtained before (Pre, black circles), immediately after the first (Post-1, dark gray circles) and second (Post-2, light gray circles) badminton match as well as after resting for 12 h (+12 h, white circles) are plotted

no specific recovery routine. From a neuromuscular perspective, competing twice on a single day during a badminton tournament may not negatively affect players' ability to produce optimal levels of MVT at the ankle joint the following day.

4.2 | Explosive strength

Our study reveals, for the first time, a downward-shift in the contractile RTD after successively playing two 35-minutes badminton matches. These changes reflect an overall fatigue-induced reduction (ranging between −15% and −20%) in rapid muscle torque characteristics for two ankle muscle groups tested. A remarkable finding was that these reductions were actually larger during earlier time intervals. Contrastingly, the effects of fatigue in response to tennis play on the contractile RTD were greater on the later phases of the rising muscle torque (>100 ms) during isometric knee extensions.[8] Nonetheless, an important consideration is that higher variability values (coefficient of variation of 5%-7% vs 13%-17%) have typically been reported for early phase EVT than for later phases of the contraction, although in the knee extensors.[19,20] Similarly, within-participant variability in our study was two-to-three-fold larger for EVT over the initial 50 ms.

We have found no previous study that analyzed the influence of a competitive match on both EVT and MVT in badminton players. Despite differences in the magnitude of RTD decrements according to the time interval considered, we observed greater EVT than MVT reductions with fatigue. This also contrasts with previous findings looking specifically at the ankle joint where no significant changes in rapid torque production capacity for the PF (ie, no data in DF), measured at similar time intervals to the present study (ie, 0-30 … 0-200 ms), occurred after playing tennis (~2 hours)[8] and football (90 minutes).[7] This may reflect that the characteristics footwork in badminton (ie, multi-directional displacements in a restricted space associated with sudden stop-and-go maneuvers and lunges) is more demanding for muscle groups of the ankle than in football or tennis. Here, explosive strength deficits in both the PF and DF may be disadvantageous for badminton players to control actions of the ankle joint during multi-directional, on-court movements (ie, longer time to reach the shuttlecock potentially with also increased effort required, altered balance and body control).

Relative RTD, which involves normalization to the MVC, is often used as a qualitative measure of explosive strength and for differentiation between potential mechanisms underlying adaptations in explosive strength after an intervention.[7,8] When normalized to MVC, we have verified that early RTD (PF: 0-100 ms; DF: 0-50 ms) decreased at Post-1 (ie, in DF) and Post-2 (ie, in both DF and PF) in reference to Pre. This would confirm that early phase explosive strength decrement is less dependent on MVT. In support, Andersen and Aagaard[21] have found a moderately positive correlation ($r = 0.45$-0.60) between the EVT in the early phase of contraction (<100 ms) and MVT. Accordingly, in the present study, the strength of the relationship between changes (data for all time point compounded) in the maximal DF/PF ratio and explosive DF/PF ratios became increasingly stronger as the time from torque onset increases.

4.3 | Ratios

Neither maximal nor explosive DF/PF ratios at all time intervals were altered by badminton play. Similar observations have been made previously in football simulated fatigue studies with no evidence of change in explosive hamstring/quadriceps ratios obtained at time intervals up to 150 ms after contraction onset.[13,14] This would confirm indirectly that, as a result of successive badminton matches, PF and DF fatigue (and recover) at a relatively similar rate.

Compared with the "traditional" maximal DF/PF ratio, explosive DF/PF ratios demonstrated significantly higher values in the early phase (< 50 ms) of contraction. During the first instants after the onset of contraction, the relative importance of DF torque in reference to PF seems greater in our badminton players. In general, values for maximal and explosive DF/PF ratios ranged from 0.53 to 0.70, which is higher than those (0.30-0.50) reported elsewhere; for example for hamstring/quadriceps ratios in skiers[22] or footballers.[12] Thus, training background seems to influence the muscle imbalance as also illustrated by previous observation of higher percentages of lower limb muscular imbalance within junior (~60%) than adult (~50%) elite soccer players.[23] This may explain the relatively high ratio values obtained in our cohort of top-level junior badminton players.

There was no difference between maximal and explosive DF/PF ratios for late-phase intervals (0-100 ms and above). These data are in partial agreement with the finding by Greco et al[13] who observed similar hamstring/quadriceps ratios (~0.60) based on peak torque and RTD values measured at 0-50 and 0-100 ms. Additionally, we observed significant relationships between the maximal DF/PF ratio and explosive DF/PF ratios at all time intervals. Such association, however, became increasingly stronger as the time interval increased. Indeed, ~74% of the variance in the maximal DF/PF ratio was explained by the explosive PF/DF ratio for the period 0-200 ms. Contrastingly, no significant correlation was reported between the maximal and explosive hamstring/quadriceps ratios in soccer players tested by Greco et al.[24] This may relate to the fact that these authors used the slope of the torque-time curve as RTD measure, with its peak values being usually attained during the window of time between 80 and 120 ms.[25] Taken as a whole, our badminton data reinforces that MVT and EVT during late time intervals share more common underlying mechanisms.[21] Future studies including electromyography recordings and percutaneous nerve electrical stimulations are required to elucidate the neural *versus* peripheral factors contributing to these badminton-induced alterations in neuromuscular function integrity.[8,18,19]

4.4 | Additional considerations and limitations

The present investigation used isometric dynamometry, and not isokinetic dynamometry, with unidirectional ankle movement at an ankle joint position of 90°, which lacks specificity in reflecting the ankle position during on-court movements. Therefore, it remains possible (but unknown) that different ankle joint configurations may affect the efficacy of the muscle-tendon unit complex and potentially leads to specific (different from isometric contractions at 90°) fatigue effects. Fatigue evaluation protocols would therefore need to assess MVT and EVT values using different ankle joint angles, contractions modes, and angular speeds. Because we assessed the dominant limb of uninjured players it also remains to be determined if lower limbs fatigue at a similar rate in badminton, especially if players have previously been injured, by comparing dominant and non-dominant sides.

5 | CONCLUSION

Successive badminton matches preferentially decrease explosive over maximal voluntary torque in both the plantar flexors and extensors but recovery is complete within 12 hours. Decrements in explosive performance with fatigue were mainly visible during the early phase of muscle contraction. Finally, muscle balance around the ankle joint was preserved.

6 | PERSPECTIVE

The present study is the first to use isometric dynamometry to differentiate between badminton-induced changes in MVT and EVT at the ankle joint. The fact that decrements in explosive muscle strength were generally double those of maximal strength in both PF and DF indicates that measuring only MVT may underestimate the functional impairment of lower extremity fatigued muscles in badminton players. This also implies that MVT and EVT are two distinct abilities that would need to be trained with different forms of resistance exercise.[4] Reportedly, the early and late phase of rising joint torque responded differently to an eccentric training program conducted for 8 weeks, demonstrating adaptations only at the very initial phase of rising joint torque (< 100 ms).[26] Because decrements in EVT in our study were more visible during early rather than late contraction phases, badminton-induced alterations in explosive performance should be analyzed using rapid muscle torque production characteristics obtained in the early phase (< 100 ms) of muscle contraction.

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CONFLICT OF INTEREST

The authors have no conflict of interest to disclose.

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