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Project title: **Changes in explosive strength after badminton match play and relationships with injury**

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EXTENDED ABSTRACT

Introduction: Success in badminton requires the ability to produce repetitive bursts of explosive efforts during on-court movements (i.e., quick lunge and return to the start or move off in another direction), characterised by high levels of muscle force/torque production within the initial phase of contraction. To date, however, muscle strength evaluation in badminton players (as in other racket sports) is mainly concerned with torque produced during maximal voluntary contractions. The aim of this study was to assess the time course of changes in maximal and rapid muscle torque production capacity of plantar flexors (PF) and dorsi flexors (DF) in response to badminton match play.

Methods: Maximal torque and rates of torque development (RTD) from 0 to 30, 0-50, 0-100, 0-100 and 0-200 ms were recorded during three maximal (3–5 s; *"as hard as possible"*) and three explosive (<1 s; *"as fast as possible"*) isometric voluntary contractions of the PF and DF (separated by ≥ 20 s), respectively. These values were obtained in sixteen juniors (10 males, 6 females), International-level badminton players before (pre-match), in-between (mid-match) as well as immediately (post-match) and 12 h (+12 h) after 70-min (2 × 35 min, 15 min of rest) badminton single matches.

Results: For both PF and DF, maximal torque decreased from pre-match to mid-match (−6.1±10.0% and −8.2±6.1%; P=0.117 and P<0.001) and post-match (−9.5±9.8% and −7.2±5.4%; P<0.001 and P=0.013), but returned near baseline after 12 h. Compared with pre-match, PF RTD decreased at mid-match (−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; 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; all P<0.001), at post-match. A similar reduction in DF RTD occurred at mid-match and post-match (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 pre-match. Reductions in RTD for both PF and DF were fully restored after only 12 h of recovery. RTD DF/PF torque ratios during the very initial phase of contraction (up to 50 ms from onset) were lower compared to the MVC DF/PF torque ratio, with no effect of time (all P<0.05).

Discussion:

- In PF and DF, decrement in explosive muscle strength are generally twice larger than in maximal strength, with most of adjustments already seen at mid-match.
- Decrements in absolute RTD were more visible during early than late contraction phases. When interpreting fatigue-induced changes in rapid muscle torque production characteristics in response to match-play badminton, alterations in contractile rates of torque development should be analysed using values obtained in the early phase (< 100 ms) of the rising muscle contraction.
- Under fatigue, early-phase (0-100 ms) contractile RTD values in both PF and DF remained lower after normalization to MVC, indicating that the physiological mechanisms underlying maximal and explosive strength during early contraction phase are not completely shared.
- Maximal and explosive strength returned near baseline after only 12 h of recovery. From a neuromuscular perspective, in a tournament scenario, playing matches on consecutive days may not negatively affect players' ability to produce optimal levels of both maximal and explosive torque in the ankle muscle groups.
- With unaltered explosive or maximal ratios, fatigue induced by badminton match play doesn't seem to reduce the potential for ankle joint stabilization during the initial phase (first 200 ms) or peak phase of voluntary muscle contractions.
- When designing rehabilitation (injury prevention) and resistance training (performance improvement) programs targeting the ankle joint of badminton players, rapid muscle torque production characteristics obtained in the early phase of the rising muscle contraction should be

prioritized.

Conclusion: Badminton decreases more rapid than maximal muscle torque production capacity of the plantar flexors and extensors. Because explosive torque indices are more sensitive (especially during < 100 ms time intervals) than 'traditional' maximal torque production capacity measurements we recommend their inclusion to more accurately reflect acute fatigue induced by a badminton match.

Key words: Badminton, Plantar flexors; Dorsi flexors; Explosive strength; Antagonist/agonist strength ratio; Fatigue; Recovery; Injury risk.

INTRODUCTION

Success in badminton requires the ability to produce repetitive bursts of explosive strength during on-court movements (i.e., quick lunge and return to the start or move off in another direction), characterised by high levels of muscle force/torque production within the initial phase of contraction. For example, a quick lunge and return to the start or move off in another direction is a common movement pattern performed during badminton competition/training, requiring rapid muscle torque production. It is therefore not surprising that badminton players possess greater quadriceps and hamstring maximal and explosive muscle strength than age-matched individuals who are physically active on a recreational basis (Andersen, Larsson, Overgaard, and Aagaard, 2007).

Muscle strength evaluation in badminton players (as in other racket sports) is mainly concerned with torque produced during maximal voluntary contractions. Because maximal torque often requires more than 300 ms to develop under isometric conditions this approach is questionable. Hence, the ability to develop force or torque rapidly (RTD or contractile rate of torque development) may be of greater importance than maximum muscle strength *per se*. In support, end-exercise reductions in RTD exceed (–15% to –25%) those in maximal strength (–10% to –12%) following a handball match (Thorlund, Michalsik, Madsen, and Aagaard, 2008) and repeated cycling sprint exercise (Girard, Racinais, and Bishop, 2013). Arguably, measuring only maximal torque production may underestimate the functional impairment of fatigued muscles. Although 'explosive' muscle strength is difficult to quantify on the court during play, it can be measured as the RTD within the early phase (i.e., rising torque) of a maximal isometric voluntary contraction (MVC) (Maffiuletti et al., 2016).

Whilst the above-mentioned reductions in explosive strength have been obtained in the knee flexors/extensors, there has been comparatively little research attention given to study plantar flexors (PF) and virtually no data available for dorsi flexors (DF). We previously examined the acute and delayed PF neuromuscular consequences of one-off football (Girard, Nybo, Mohr, and Racinais, 2015) or tennis (Girard, Racinais, and Périard, 2014) matches in semi-professional players. In football, acute match-related changes in explosive torque production in PF were seen in the very early phase (0–30 ms epoch) of the contraction, with no change at any other epochs. In tennis, explosive muscle strength and activation capacity of the PF were preserved in response to prolonged (~2 h) match-play tennis.

In badminton, the actions of the PF muscle compartment 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. Under fatigue, any changes in maximal muscle strength or delayed contraction onset (*i.e.*, RTD) would be expected to negatively impact explosive-type actions typically seen in badminton (e.g., sharp accelerations, decelerations, jumps, leaps, lunges and rapid directional changes) and increase the incidence of injuries. A sprained ankle is the single most common injury in badminton (Jorgensen and Winge, 1990; Reeves, Hume, Gianotti, Wilson, Ikeda, 2015). Hence, the rapid changes in direction that are required during badminton can cause the ankle to roll over, particularly if the player is fatigued. Furthermore, little is known about the recovery of both maximal and rapid torque capacities in this muscle group in the hours after competing.

The influence of Hamstrings/Quadriceps strength imbalance on knee injury risk is well described. Previous studies have traditionally identified strength deficits through the assessment of maximal knee flexor and knee extensor strength (usually achieved > 300 ms after the onset of contraction) by calculating the MVC Hamstrings/Quadriceps ratio. Recently, the ratio of rapid isometric Hamstrings *versus* Quadriceps torque production (RTD ratio) assessed over shorter time frames (< 200 ms) has been proposed as a relevant measure of dynamic knee joint stabilization (Zebis, Andersen, Ellingsgaard, and Aagaard, 2011). Although several studies have examined the RTD Hamstrings/Quadriceps ratio, these investigations mainly focused on injured athletes such as ACL-reconstructed elite Alpine ski racers (Jordan, 2015). In comparing the RTD Hamstrings/Quadriceps ratio among professional soccer players who have heterogeneous values for MVC Hamstrings/Quadriceps ratio, Greco, Da Silva, Camarda, and Denadai (2013) failed to observe significant correlations between these indices, suggesting that their physiological and clinical meanings may be different. To date, however, no previous study has determined these antagonist/agonist ratios for the ankle muscle groups and how this is (or not) affected by fatigue, for instance induced by badminton match play.

Our intention was to assess the time course of changes in maximal and rapid muscle torque production capacity of the ankle plantar flexors (PF) and dorsi flexors (DF) in response to badminton match play. We hypothesized that playing badminton would induce larger impairments in RTD in reference to MVC torque.

METHODS

Experimental Approach to the Problem

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 as per the *Journal of Strength and Conditioning Research* author guidelines. 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).

Participants

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 familiarised with the testing procedures and neuromuscular function assessment protocol until they felt accustomed with the equipment [*i.e.*, coefficient of variation in three successive MVC and RFD (200 ms after contraction onset) trials lower than 3% and 5%, respectively]. This was followed after ~10 min of rest by the baseline neuromuscular function assessment, while similar tests were completed during (during the 15-min break between the two match segments), immediately and 12 h (following morning between 9 and 10 am) after badminton match play (see below).

Badminton match play

Opponents were matched for performance ability and gender. After an individual warm-up of about 10 min, subjects played a match of two 35 min segments with 15 min rest in between (total of 85 min). 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 players. The players were supplied with pure water at the sidelines with ad libitum intake during the games, but no artificial breaks were provided.

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 s) and separated by ≥ 30 s of rest. Participants were instructed to increase torque production over a 1-s period, hold it for 3–4 s and then relax before completing the next contraction. Thereafter, participants were instructed to perform three “explosive” MVCs (separated by ≥ 20 s) where participants were carefully instructed to contract “as fast as possible” for ∼1 s 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; *i.e*. they were reminded not to dorsiflex the foot immediately prior to plantar flexion *(and vise versa)*. Contractions that had any discernable countermovement or pre-tension (*i.e*. change of baseline torque of > 0.5 Nm during the 100 ms before contraction onset; Girard, Racinais, and Périard, 2014) 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. Baseline and 12 h post-match assessments were preceded by a standardized warm-up consisting of 10 isometric PF / DF (alternating 4 s of contraction and 6 s of rest). Contraction intensity was progressively self-adjusted by the subject to attain maximal torque in the last three contractions.

Picture 1 – Experiment set-up used to assess voluntary/explosive strength production capacity in the plantar flexors and dorsi flexors.

Torque measurements

Isometric plantar flexion / dorsi flexion 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 (Picture 1). 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).

Data analysis

The MVC torque was defined as the maximum value recorded for 1 s 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 (i.e., $RTD_{0\text{-}30}$, $RTD_{0\text{-}50}$, $RTD_{0\text{-}100}$, $RTD_{0\text{-}150}$, and $RTD_{0\text{-}200}$, respectively), relative to the onset of contraction using a custom written program (Spike 2 Software, Cambridge Electronic Design, Cambridge, UK). In addition, raw RFD data were normalized relative to MVC torque (%MVC). For both maximal and explosive contractions, the average of three trials was used for further analysis.

Finally, DF torque was expressed relative to PF torque to produce ratios of MVC DF/PF torque and RTD DF/PF torque. Specifically, RTD DF/PF torque ratios were calculated by dividing DF RTD with PF RTD in the examined time period (i.e., 0-30, 0–50, 0–100, 0–150 and 0–200 ms, for example, DF $RTD_{0\text{-}100}$ divided by PF $RTD_{0\text{-}100}$, etc) (Zebis, Andersen, Ellingsgaard, and Aagaard, 2011).

Statistical analysis

Values are expressed as means±SD. Two-way repeated measures analysis of variances [Time (pre-match, mid-match, post-match and +12 h) × 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. MVC and RTD 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 $P<0.05$.

RESULTS

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

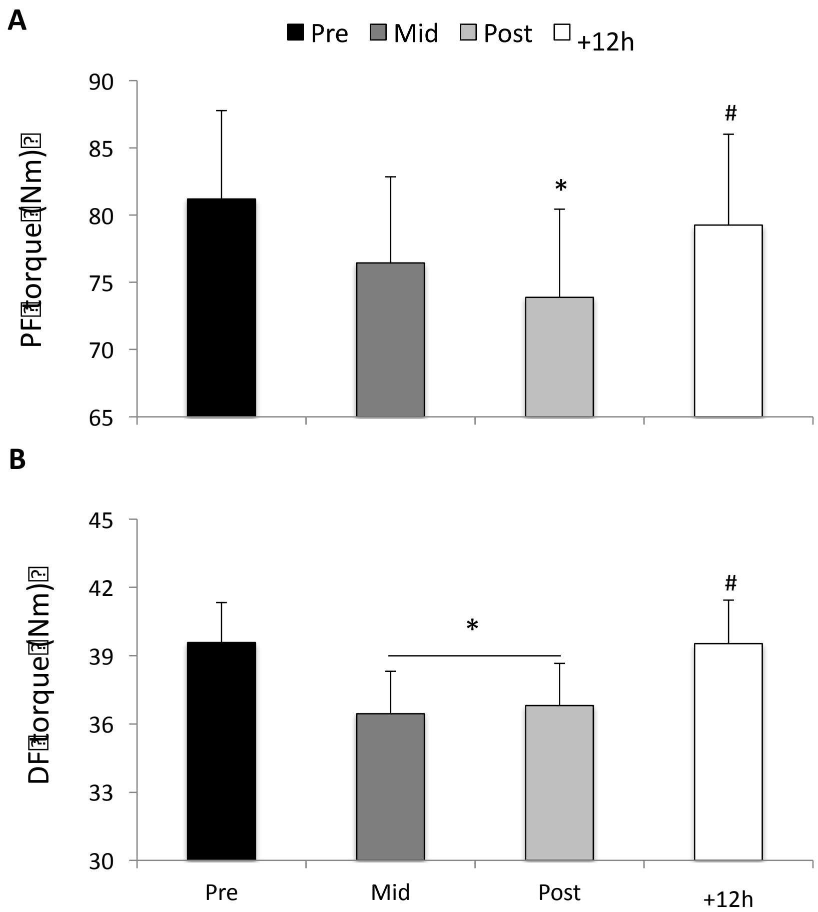

Figure 1 – Maximal isometric voluntary contraction torque in plantar flexors (A) and dorsi flexors (B) before (Pre), during (Mid) as well as immediately (Post) and 12 h (+12 h) after badminton match play *(n=16)*.
** significantly different from Pre. # significantly different from previous time interval.*

Compared with pre-match, PF RTD decreased at mid-match (–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; 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; all $P<0.001$), at post-match (Figure 2). A similar reduction in DF RTD occurred at mid-match and post-match (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 pre-match. Reductions in RTD for both PF and DF were fully restored after only 12 h of recovery.

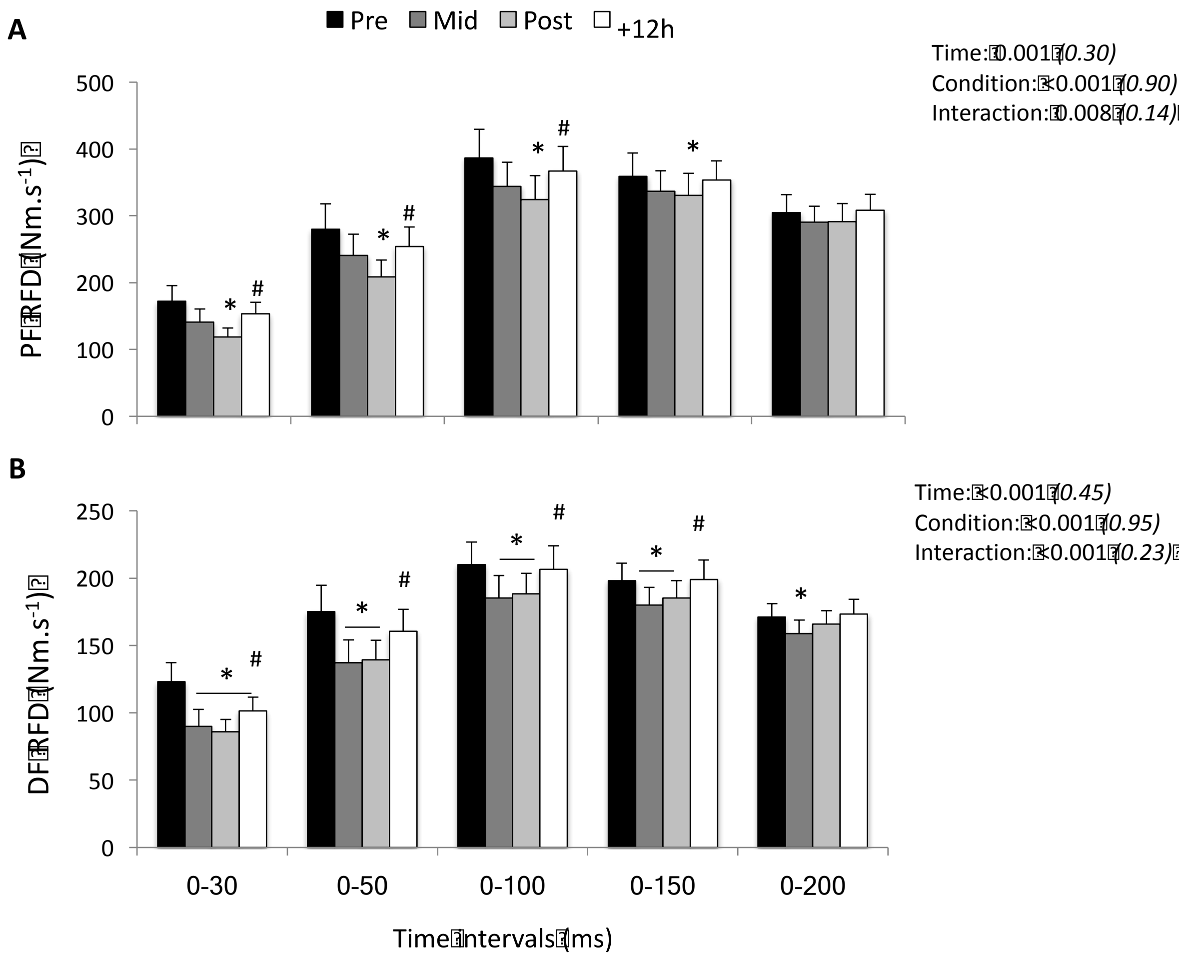

Figure 2 – Rate of torque development during explosive isometric plantar flexions (A) and dorsi flexions (B) obtained at 0-30, 0-50, 0-100, 0-150 and 0-200 ms before (Pre), during (Mid) and immediately (Post) and 12 h (+12 h) after badminton match play *(n=16)*.
** significantly different from Pre. # significantly different from previous time interval.*

Normalized PF RTD decreased at post-match 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; all $P<0.05$) relative to pre-match. Compared to pre-match, DF normalized RTD was reduced mid-match, post-match and +12-h (–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 mid-match (–15.5±15.4%; $P<0.05$) and post-match (–12.4±13.1%; $P<0.05$).

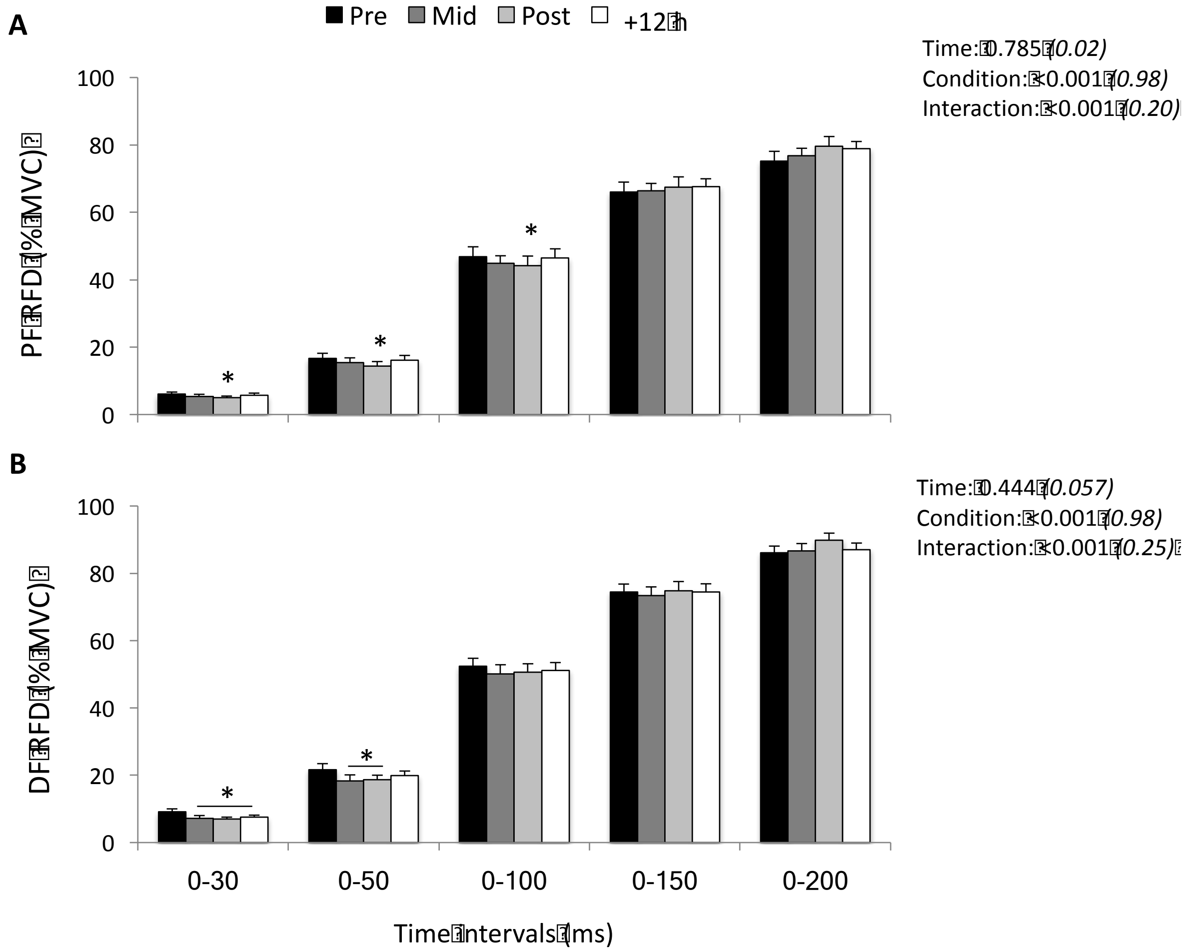

Figure 3 – Normalized rate of torque development during explosive isometric plantar flexions (A) and dorsi flexions (B) obtained at 0-30, 0-50, 0-100, 0-150 and 0-200 ms before (Pre), during (Mid) and immediately (Post) and 12 h (+12 h) after badminton match play *(n=16)*.
** significantly different from Pre. # significantly different from previous time interval.*

There was no significant effect of time on MVC DF/PF ratios (0.52±0.13, 0.52±0.21, 0.55±0.20 and 0.54±0.17, respectively; P = 0.502; η=0.050). The average MVC DF/PF torque ratio for the collapsed match time points was 0.53±0.17. Whereas there was no significant time (P=0.507; η=0.05) or analysis epoch × time (P= 0.706; η=0.05) interaction, RTD DF/PF ratios differed according to the analysis epochs considered (P<0.001; η=0.39) (Figure 4). Post hoc tests showed higher values (P<0.001) for RTD DF/PF torque ratio during the very initial phase of contraction (up to 50 ms from onset) compared to the MVC DF/PF torque ratio.

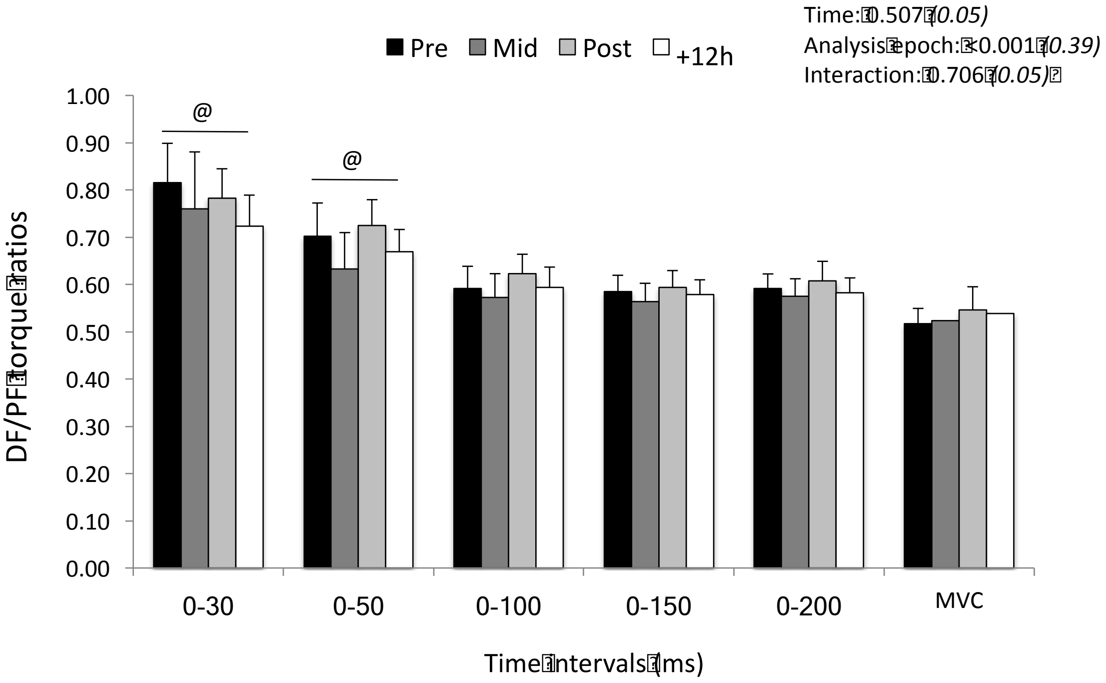

Figure 4 – Dorsi flexion/plantar flexion (DF/PF) torque ratios obtained at 0-30, 0-50, 0-100, 0-150 and 0-200 ms during explosive contractions (RFD) and during maximal voluntary contractions (MVC) before (Pre), during (Mid) and immediately (Post) and 12 h (+12 h) after badminton match play *(n=16)*.
@ significantly different from MVC.

In general, moderate to strong correlation was observed between MVC DF/PF and RTD DF/PF torque ratios, with correlation coefficient between these parameters increased as the time from the onset of contraction increased ($RTD_{0\text{-}30}$: r=0.38, P=0.002; $RTD_{0\text{-}50}$: r=0.43, P<0.001; $RTD_{0\text{-}100}$: r=0.64, P<0.001; $RTD_{0\text{-}150}$: r=0.74, P<0.001; $RTD_{0\text{-}200}$: r=0.81, P<0.001). An example of correlation between MCV and $RTD_{0\text{-}200}$ DF/PF torque ratios is given in Figure 5, where the explained variance was 74%.

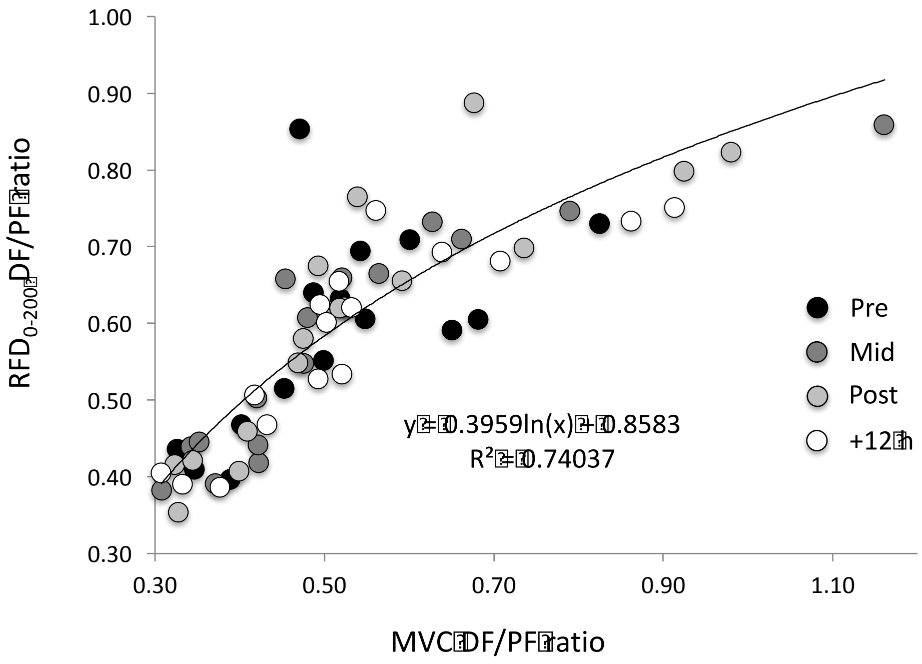

Figure 5 – Relationship between dorsi flexion/plantar flexion (DF/PF) torque ratios obtained at 0-200 ms (RFD_{0-200}) and during maximal voluntary contractions (MVC). Data obtained before (Pre, black circles), during (Mid, dark grey circles) and immediately (Post, light grey circles) and 12 h (+12 h, white circles) after badminton match play are plotted *(n=16)*.

DISCUSSION

In badminton, the repetition of rapid and intense leg movements such as lunging, jumping, changing direction and a wide range of body postures, likely cause fatigue in lower limbs. Our study is the first to profile the neuromuscular fatigue response to 70 min of badminton match play, with special reference to rapid muscle strength capacity in ankle muscle groups. In agreement with our hypothesis, impairments in ankle joint voluntary strength for both the PF and DF during and immediately after match-play badminton were twice larger during explosive compared to maximal contractions, recovering fully within 12 h.

Maximal strength

From a neuromuscular perspective, muscle fatigue is defined as an exercise-induced reduction in the maximum capacity of the muscle to generate/maintain force or power (Gandevia, 2001). In this study, maximal torque generated by the ankle muscle groups (i.e., relatively similar magnitude of strength losses in PF and DF) decreased from pre- to mid-match (–6-8%) with little additional decrement recorded at match-end (–7-9%). These data suggest that the badminton match produced muscle fatigue in either the PF or DF and that this fatigue develop quite rapidly since most of the alterations are already seen after playing for only 35 min. Differently, we previously observed that PF voluntary torque assessed every 30 min during a 3-h tennis match followed a biphasic pattern with a slight but significant decrease in PF MVC torque after 90 min (~−4%) and a further marked decrease after 3 h (~−15%) (Girard, Racinais, Micallef, and Millet, 2011). While no data exist 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 (Nybo et al., 2013) or tennis (Girard, Racinais, and Periard, 2014) players are rather modest and not significant. Additionally, Abian-Vicen, Del Coso, Gonzalez-Millan, Salinero, and Abian (2012) did not observe pre-post badminton game difference for height (that actually increased by 4.5%) and mean power in the push-off phase of counter-movement jumps. Previous tennis (Ojala and Häkkinen, 2013) and football (Thornlund, Aagaard, and Madsen, 2009) findings indicate that countermovement jump was not reduced from pre- to post-match, whereas knee extensors MVC (and RTD) was. Important methodological difference between studies (nature of the test conducted to assess leg fatigue, nature and characteristics of the simulated game) might explain the disparity between the results. Thus, caution should be exercised when making comparisons between studies.

It is suggested that sources proximal (i.e., central fatigue) and distal (i.e., peripheral fatigue) to the neuromuscular junction modulate these decrements in MVC torque. Studies that used percutaneous nerve stimulations to shed more light on potential fatigue-causing mechanisms have been carried out in other racket sports, mainly tennis (Girard and Millet, 2009), and have found that strength losses in lower extremities may develop as a match progresses because of suboptimal muscle activation. Alternatively, development of fatigue manifested by mistimed strokes, lower speed, and altered on-court movements may also be caused by ionic disturbances and impairments in excitation-contraction coupling properties (Girard and Millet, 2009). Because measures of central and peripheral fatigue were not conducted it was not possible here to determine the exact nature of underpinning mechanisms causing maximal torque to decrease in both PF and DF. While additional studies are needed to confirm the etiology of fatigue in badminton, our unique findings indicate that a large part of decrement in MVC is already achieved after 35 min of play. Another important observation also was that maximal voluntary strength capacity for the two ankle muscle groups recovered quickly. Indeed, MVC torque values returned near baseline only after a night of rest (12 h) with no specific recovery routine.

Explosive strength

Our study reveals, for the first time, a downward-shift in the contractile RTD during and following match-play badminton (i.e., after playing for 35 and 70 min, respectively). These changes reflect an overall fatigue-induced reduction (range −15-20%) in rapid muscle torque characteristics for two muscle groups tested. A remarkable finding was that these reductions were actually larger during earlier time intervals, which may negatively affect functional performance during on-court movements. Indeed, 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 (i.e., longer time to reach the shuttlecock potentially with also increased effort required, altered balance and body control). Contrastingly, the effects of fatigue in response to tennis match play on the contractile RTD were increasingly clear on the later phases of the rising muscle torque during isometric knee extensions. Andersen and Aagaard (2006) have shown that RTD is influenced by different factors at early (< 100 ms: neural drive and intrinsic muscle contractile properties) and late phases (> 100 ms: neural, muscle cross-sectional area and tendon/aponeurosis stiffness) from the onset of muscle contraction. The preferential reduction in RTD in the early than the late phase of muscle contraction would indicate that both central and peripheral mechanisms are involved.

We have found no previous study that analyses the influence of a competitive match on both explosive and maximal muscle strength in badminton players. Despite the differences in which

RTD interval displayed the greatest decrease, we observed more pronounced (i.e., twice larger) RTD-type fatigue in reference to MVC torque. This also contrasts with previous findings, looking specifically at the ankle joint; no significant changes in rapid torque production capacity for the PF (i.e., no data in DF), measured at similar time intervals as in the present study (i.e., 0-30 … 0-200 ms), occurred after playing tennis (~2 h; Girard, Racinais, Periard, 2014) and football (90 min; Girard, Nybo, Mohr, Racinais, 2015). This is taken to reflect that the characteristics footwork in badminton (i.e., multidirectional displacements in a restricted space associated with sudden stop-and-go maneuvers and lunges) is probably more demanding for the ankle muscle groups than in football or tennis.

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. When normalized to MVC, we have verified that early RTD (PF: 0-100 ms; DF: 0-50 ms) decreased during (i.e., in DF) and after (i.e., in both DF and PF) the match. This would confirm that early phase explosive strength decrement is less dependent on maximal voluntary torque capacity. Said differently, the physiological mechanisms underlying maximal torque and RTD recorded during early contraction phase of DF and PF under fatigue state are not completely shared. In support, Andersen and Aagaard (2006) have found a moderately positive correlation ($r = 0.45$-0.60) between the RTD in the early phase of contraction (< 100 ms) and maximal torque. Accordingly, in the present study, the strength of the relationship between changes (data for all time point compounded) in explosive (RFD) and maximal (MVC) DF/PF ratios became increasingly stronger as the time from torque onset increases.

Ratios

Fatigue might increase the susceptibility of a player to injury, particularly as a result of consecutive intense rallies or towards the end of a match. To date, only one published study has assessed the effect of fatigue induced by an exhaustive laboratory-based soccer-specific exercise on RTD ratios obtained during the early contraction phase (50 and 100 ms after contraction onset) and found no differences between pre- and post-exercise conditions (Greco, da Silva, Camarda, and Denadai, 2013). Similar to found in the aforementioned study, maximal and explosive ratios at all time intervals were not altered by match-induced fatigue. This would confirm indirectly that, as a result of badminton match play, PF and DF fatigue (and recover) at a relatively similar rate.

Compared to ‘traditional’ MVC ratio, RTD ratios demonstrated significantly higher values in the early phase (< 50 ms) of rising muscle torque. This reflects that, during the first instants after the onset of contraction, the relative importance of DF torque in reference to PF is greater. Due to the constraints of the game, the elevated RFD DF/PF ratios for 0-30 and 0-50 ms time intervals is an important neuromuscular characteristic of our top-level badminton players who are able to develop a better DF/PF muscle strength balance over the initial phase of torque rise in isometric contractions. In our study, RTD and MVC DF/PF ratios ranged from 0.53 to 0.70, which is higher than values (0.30-0.50) reported elsewhere, for instance, for Hamstring/Quadriceps ratios in skiers (Jordan, Aagaard, and Herzog, 2015) or footballers (Zebis, Andersen, Ellingsgaard, Aagaard, 2011). Thus, training background seems to influence the muscle imbalance. Higher percentages of lower limb muscular imbalance were previously reported within junior (~60%) than adult (~50%) elite soccer players (Lehence, Binet, Bury, and Croisier, 2009). This may offer an explanation for the relatively high ratio values obtained in our cohort of junior badminton players. Outside the fact that different muscle groups are tested (knee *vs*. ankle) between the present and other studies, comparisons with literature are also difficult due to the use of isometric *vs*. dynamic dynamometry (with also different contraction modes and angular velocities), recruitment of athletes with various background as well as utilization of specific calculation methods or different time intervals for RTD determination.

Interestingly, there was no difference between MVC ratio and RTD ratios for late-phase intervals (0-100 ms and above). These data are in partial agreement with the finding by Greco, da Silva, Camarda, and Denadai (2013) who observed similar Hamstring/Quadriceps ratios (~0.60) based on peak torque and RTD at 0-50 and 0-100 ms values. Moreover, we observed that association of MVC ratio with RTD ratios was significant for all time intervals but became increasingly stronger as the time interval increased. Indeed, 74% of the variance in MVC ratio was explained by $RTD_{0\text{-}200}$ ratio. Contrastingly, a lack of any significant correlation between the maximal and explosive Hamstring/Quadriceps ratios was observed in the soccer players tested by Greco et al. (2013). This may relate to the fact that these authors used the slope of the torque-time curve as RTD measure, with its maximal values being usually attained during the window of time between 80 and 120 ms (Aagaard et al., 2002). Taken as a whole, this reinforces that MVC and RTD during late time intervals share some common underlying mechanisms.

Additional considerations and limitations

The present investigation used isometric dynamometry, and not isokinetic dynamometry, to assess the dominant limb of uninjured players. Future studies should determine whether similar or perhaps larger changes occur using dynamic contractions and if lower limbs fatigue at a similar rate by comparing dominant and non-dominant sides. Indeed, there is a possibility that explosive strength leads to larger fatigue-induced changes in muscle strength, especially if players have previously suffered a lower limb injury. Assessing bilateral leg asymmetry using explosive strength measures would also be relevant to monitor long-term adjustments in neuromuscular function and eventually detect when fatigued players are at a higher risk of injury.

In our study, PF and DF torque measurements were evaluated under isometric conditions (unidirectional ankle movement) at an ankle joint position of 90°, which may not necessarily reflect the position of the foot where injury occurs on the court. It remains possible (but unknown) that different ankle joint configurations affect the efficacy of muscle-tendon unit complex and potentially leads to specific (different from isometric contractions at 90°) fatigue effects. Fatigue evaluation protocols would therefore need to test explosive and maximal strength using different ankle joint angles, contractions modes and angular speeds (concentric and eccentric actions).

PRACTICAL APPLICATIONS

Imbalances between the antagonist and agonist muscles has been traditionally assessed by "conventional" concentric Antagonist/Agonist ratio or "functional" eccentric Antagonist/Agonist ratio) derived from peak torque values during a MVC (Camarda and Denadai, 2012). However, time spans involved in most explosive, on-court badminton movements may not allow maximal torque to be reached; it usually requires more than 300 ms to develop under isometric conditions. Additionally, there is a short time history of non-contact injury in badminton (< 100 ms after foot contact). Consequently, calculating Antagonist/Agonist ratios from peak torque values is questionable in badminton. Instead, the RTD 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 during explosive movements (Zebis, Andersen, Ellingsgaard, and Aagaard, 2011). While previous studies have almost exclusively investigated the Hamstring/Quadriceps ratio there are no published reference values for RTD ratios for the ankle joint. The present study is the first to use isometric dynamometry to differentiate between maximal and explosive strength (RTD) in the ankle muscle groups. To achieve effective injury prevention, it is important to identify modifiable risk factors that can be targeted through exercise and training. Because RTD and maximum muscle strength are relevant to dynamic athletic performance and can be developed by specific training methods, assessment of these strength characteristics may provide important information for optimizing the design of rehabilitation and resistance training programs, for instance in previously injured badminton players. In doing so, early phase (< 50 ms) explosive DF/PF ratios might be useful in identifying players at a potentially greater risk of injury.

The larger deficits in explosive *vs*. maximal torque indicate that these are two distinct abilities that would need to be trained with different forms of resistance exercise. Reportedly, eight weeks of maximal eccentric resistance training of the knee extensors led to marked gains in maximal isometric muscle torque production (Oliveira, Corvino, Caputo, Aagaard, and Denadai, 2016). However, the early and late phase of rising joint torque measured by the contractile RTD responded differently to the eccentric training programme, demonstrating adaptations only at the very initial phase of rising joint torque (< 100 ms). Our badminton results indicate that alterations in RTD with fatigue were mainly visible during the early phase of muscle contraction. While these findings need to be confirmed for the ankle joint, eccentric training represents a useful resistance exercise training modality for badminton players to improve fatigue resistance. Such training modality may also reduce the risk of injury by preventing excessive load and relevant badminton injuries through optimal shock attenuation and movement stabilization.

CONCLUSION

Badminton decreases more rapid than maximal muscle torque production capacity of the plantar flexors and extensors. Because explosive torque indices are more sensitive (especially during < 100 ms time intervals) than 'traditional' maximal torque production capacity measurements we recommend their inclusion to more accurately reflect acute fatigue induced by a badminton match.

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