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Relevance of evaluating the rate of torque development in ballistic contractions of submaximal amplitude.

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ABBREVIATIONS

MVT: Maximal Voluntary Torque

$RTD_{maximal}$: Rate of Torque Development during maximal contraction

$RTD_{submaximal}$: Rate of Torque Development during submaximal contraction

RTD-SF: Rate of Torque Development Scaling Factor

Abstract

Objective: The neuromuscular quickness capacity can be assessed calculating the rate of torque development (RTD) during ballistic contractions of maximal ($RTD_{maximal}$) or submaximal ($RTD_{submaximal}$) amplitudes. In a series of ballistic contractions of submaximal amplitudes, RTD scaling factor (RTD-SF) represents the slope of the linear regression between achieved peak torques and the corresponding RTD. We firstly investigated if the RTD-SF contributes to predict, together with maximal voluntary torques (MVT), the $RTD_{maximal}$. Then, we evaluated the agreement between the z-scores of $RTD_{maximal}$ and $RTD_{submaximal}$.

Approach: MVT of quadriceps and hamstrings muscles were obtained in 22 elite young soccer players. RTD-SF was quantified in a series of ballistic contractions of submaximal and maximal amplitudes. $RTD_{submaximal}$ was estimated from the regression relationship between the peak torques and the corresponding RTD.

Main results: MVT, RTD-SF and y-intercept accounted all together for 76.9 and 61.2% of the variance in $RTD_{maximal}$ in quadriceps and hamstrings, respectively. Specifically, RTD-SF accounted for 13.7% and 18.7% of the variance in $RTD_{maximal}$ respectively. Generally, the agreement between the z-scores of $RTD_{maximal}$ and $RTD_{submaximal}$ was poor both in quadriceps and hamstrings.

Significance: These results suggest that RTD-SF may have a functional relevance in the relationship between MVT and $RTD_{maximal}$ and influence the amount of torque that can be achieved in a quick muscle contraction. Moreover, evaluating the $RTD_{submaximal}$ does not provide interchangeable results with $RTD_{maximal}$. Thus, evaluating the RTD across the whole range of torque could provide additional meaningful information about neuromuscular quickness.

Keywords: Rate of torque development scaling factor; explosive contraction; soccer.

Introduction

Maximal voluntary torque (MVT) is typically measured adopting a 5-s maximum contraction at a specified joint angle against an unyielding resistance and represents an easy, reliable, and valid method to quantify muscular function in a variety of research settings (Wilson and Murphy, 1996). However, MTV does not reflect the muscle abilities necessary in everyday life (e.g., walking, climbing, going down stair) as well as in sport activities (Aalund *et al.*, 2013; Maffiuletti *et al.*, 2016). Indeed, peak torque typically occurs at 300ms or more after the onset of isometric contraction (Rodríguez-Rosell *et al.*, 2017), while in sport context the time available for torque development is often limited to 50-250 ms (Tillin *et al.*, 2010; Andersen and Aagaard, 2006). Thus, the ability to rapidly exert high levels of muscle torque is a fundamental quality to maximize sport performance (Maffiuletti *et al.*, 2016). This ability can be measured through the rate of torque development (RTD).

RTD is often calculated as the maximum of the torque–time curves derivative (Aagaard *et al.*, 2002; Maffiuletti *et al.*, 2016; Rodríguez-Rosell *et al.*, 2017; Djordjevic and Uygur, 2017) and is considered an important aspect of neuromuscular function where time for torque development is limited, as in running, jumping, sprinting or kicking (Buckthorpe and Roi, 2017; Tillin *et al.*, 2010; Aagaard *et al.*, 2002; Chang *et al.*, 2015; Boccia *et al.*, 2018b). Compared to MVT, RTD ability seems to be more sensitive to adaptations in the neuromuscular system (Peltonen *et al.*, 2018; Penailillo *et al.*, 2015; Jenkins *et al.*, 2014; Mirkov *et al.*, 2017). For example, RTD has been considered a more specific and sensitive indirect marker of muscle damage than MVT (Penailillo *et al.*, 2015). Moreover, RTD has suggested to be a factor involved in non-contact injury mechanisms (Mirkov *et al.*, 2017) as well as an informative measure to safely decide the return to sport (Angelozzi *et al.*, 2012). For these reasons, RTD has been recently proposed to be incorporated during the rehabilitation process after sport injuries (Buckthorpe and Roi, 2017).

To evaluate the RTD, the most widely adopted method is to ask participants to isometrically contract their muscles as fast and hard as possible against an unyielding resistance (Sahaly *et al.*, 2001). Throughout the manuscript we will refer to the RTD extracted with this procedure as $RTD_{maximal}$. However, the RTD can also be evaluated asking the participants to (roughly) reach submaximal torques as quick as possible, thus performing a ballistic contraction of submaximal amplitude (Bellumori *et al.*, 2011; Djordjevic and Uygur, 2017; Casartelli *et al.*, 2014; Bellumori *et al.*, 2013; Haberland and Uygur, 2017). Throughout the manuscript we will refer to the RTD extracted with this procedure as $RTD_{submaximal}$.

In a series of ballistic contractions of submaximal amplitude a higher target torque yields a higher RTD produced by the subject (Bellumori *et al.*, 2011, 2013; Casartelli *et al.*, 2014; Djordjevic and Uygur, 2017). In particular, a robust positive linear relationship has been observed between the peak torque and RTD of the corresponding contraction (Bellumori *et al.*, 2011, 2013; Casartelli *et al.*, 2014; Djordjevic and Uygur, 2017; Haberland and Uygur, 2017). The slope of this regression is named RTD scaling factor (RTD-SF) and quantifies the scaling of the RTD with the amplitude of contraction. Moreover, the obtained R^2 provides the consistency in performing rapid muscular contractions with the magnitude of the produced force (Haberland and Uygur, 2017; Bellumori *et al.*, 2011). A high scaling factor, along with R^2 values close to 1, provides a relative invariance in the time required to reach peak torque regardless of contraction amplitude (Bellumori *et al.*, 2013; Haberland and Uygur, 2017; Mathern *et al.*, 2018). Differently to MVT and $RTD_{maximal}$, RTD-SF is similar in both genders, relatively constant across muscles with different strength, and independent from muscle fatigue (Bellumori *et al.*, 2011; Haberland and Uygur, 2017; Maloney, 2018; Boccia *et al.*, 2018b). Consequently RTD-SF may facilitate comparisons among different populations (Bellumori *et al.*, 2011; Haberland and Uygur, 2017; Chou *et al.*, 2013).

Despite the inherent differences, there is an association between MVT and $RTD_{maximal}$. The strength of this association depends on the time instant in which the RTD is calculated from the onset of the contraction. The early phase of RTD, i.e. the first 50 ms of a muscle contraction, is poorly correlated to MVT, while the late phase of RTD, i.e. later than 100 ms, is strongly correlated to MVT (Folland *et al.*, 2014; Andersen and Aagaard, 2006). Specifically, MVT explains from 30 to 60% of the variance in $RTD_{maximal}$ (usually reached at 70-100 ms after the onset of a contraction) (Folland *et al.*, 2014; Andersen and Aagaard, 2006). Although RTD-SF is independent of MVT, it is plausible that it could influence the amount of achievable torque in a quick muscle contraction. Indeed, the RTD-SF regulates the quickness of ballistic contraction across the whole range of torque amplitudes. Consequently, we can hypothesize that RTD-SF may contribute, together with MVT, to explain variance of $RTD_{maximal}$. Nevertheless, to date this hypothesis has never been tested. To test this hypothesis, it may be interesting to understand the functional relevance of the RTD-SF to explain the variance in $RTD_{maximal}$.

The RTD-SF protocol provides the possibility to assess the ability for quickly producing torque of submaximal amplitude (Bellumori *et al.*, 2011; Djordjevic and Uygur, 2017; Casartelli *et al.*, 2014; Bellumori *et al.*, 2013). As previously suggested (Haberland and Uygur, 2017; Bellumori *et al.*, 2017; Park and Stelmach, 2007; Gordon and Ghez, 1987), this may be particularly relevant for many daily life activities and sports where a quick production of submaximal torque is crucial for object manipulation or body propulsion. However, it is important to understand if the information that can be gathered in this protocol is related to what can be obtained through the classical method for measuring $RTD_{maximal}$, i.e. producing a muscle contraction as fast and hard as possible. For this reason, it seems important to quantify the level of agreement between the $RTD_{maximal}$ (the classical method) and the $RTD_{submaximal}$ obtained with RTD-SF protocol (the herein proposed method).

To fill the above-mentioned gaps in the literature, we wanted to provide more data about the relationship between the capacity to produce ballistic contractions of maximal compared to submaximal amplitude. Thus, the experimental questions were the following: 1) to delineate the importance of RTD-SF in predicting $RTD_{maximal}$ in quadriceps and hamstrings muscles; 2) to evaluate the level of agreement between the $RTD_{maximal}$ and $RTD_{submaximal}$ at different submaximal amplitudes. Moreover, as exploratory analysis, we wanted to investigate the relationship between RTD-SF and normalized $RTD_{maximal}$ (i.e., $RTD_{maximal}$/MVT). Indeed, similarly to RTD-SF, normalized $RTD_{maximal}$ is a measure of neuromuscular quickness independent to MVT. For this reason, it would be interesting to understand the extent of association between these two measures.

Material and Methods

Participants

This study was a further analysis of the data collected for a previously published study (Boccia *et al.*, 2018a). Here we maintained the same experimental footprint, but with different research questions. Twenty-two elite young soccer players (age 17 ± 1 years, range: 16-18 years; body mass 72 ± 9 kg; height 1.82 ± 0.08 m) participated in this study. The participants joined under-17 and under-19 teams competing in the Italian soccer championship. All the participants were healthy, without cardiac or pulmonary diseases, as certified by the club's medical staff. If players suffered knee, ankle or hip injury on one or both legs in the previous six months, the involved leg was excluded from the present investigation. The study was performed during the pre-season.

All participants provided their written informed consent before the experiments. Written parental/legal guardian consent was also obtained for participants younger than 18 years old. The study was approved by the local Ethical Committee and performed in accordance with the Declaration of Helsinki.

Data acquisition

Measurements were conducted using an isokinetic dynamometer (BIODEX System 3 Biodex Medical System, NY USA). The device was calibrated and the gravity correction executed according to the manufacturer's procedures. The participants were seated with their trunk reclined 85° and knee joints were at approximately 90° of flexion and secured by seatbelts (i.e., across the chest, pelvis) to minimize body movements during the trials (Maffiuletti *et al.*, 2007). Mid-thigh and tibia were secured using non-elastic straps and knee joints were aligned with the centre of rotation of the dynamometer. The padding from the arm was removed to provide virtually isometric conditions and minimize baseline noise (Bozic *et al.*, 2013; Maffiuletti *et al.*, 2016). Data were recorded for quadriceps and hamstrings of both dominant and non-dominant limbs. We pooled the results of the two limbs because each limb was considered as a separate case. Thus, we included in the analysis a total of 41 and 42 cases for quadriceps and hamstrings respectively. The limb order was randomized, while quadriceps was always tested before hamstrings. For all trials a real-time visual feedback of the torque output (display as vertical bar graph) as a percentage of maximal force (% MVT) was provided on a computer screen placed at eye level (Bellumori *et al.*, 2017).

Procedure

Each participant completed the test session, including 1) maximal voluntary isometric contractions and 2) RTD-SF protocol in one day. The same investigators conducted the test session. The warm up consisted of 10 minutes of cycling at 75 W and 10 submaximal isometric contractions (at intensities from 20 to 60% of perceived maximum contraction) for quadriceps and hamstrings.

To measure the MVT, participants performed two 3-s maximal voluntary isometric contractions interspersed by 60-s rest. Participants were verbally encouraged to contract at maximal torque.

The RTD-SF protocol started one minute after the last maximal voluntary contraction. The RTD-SF relationship was computed from sets of several pulses (i.e., ballistic isometric contractions) performed across a full range of amplitudes (Freund and Budingen, 1978; Wierzbicka *et al.*, 1991; Klass *et al.*, 2008). Participants were instructed to perform four to six ballistic isometric contractions at five approximate amplitudes presented in an ascending order (20, 40, 60, 80, and 100% calculated with respect to the highest recorded MVT). The rest interval between contractions was 4 s (Fig. 1a). According to Bellumori and colleagues (2011, 2013), participants were explicitly instructed to produce each isometric torque pulse as quickly as possible and then relax instantly. During the execution of the protocol the emphasis was on the quickness of the contraction rather than on the accurateness (Boccia *et al.*, 2018b). Thus to avoid slowing down the rate of product torque, an explicit instruction, not to focus on the required strength levels, was given (Gordon and Ghez, 1987). For this reason, participants were explicitly instructed to contract as fast as possible so that the peak torques could approximately reach a 10% range around the given torque target (black horizontal lines) displayed on the online visual feedback of computer screen. Before starting the RTD-SF protocol, participants practiced a familiarization session until they felt comfortable with the task and could perform discrete ballistic contractions as instructed (Casartelli *et al.*, 2014; Bellumori *et al.*, 2013, 2011; Boccia *et al.*, 2018b).

Data analysis

Mechanical signals

All data were analysed by custom-written software in MATLAB R2017a (Mathworks, Natick, Massachusetts). The torque signal was sampled at 2048 Hz, converted to digital data with a 12-bit A/D converter (EMG-USB2+, OT Bioelettronica, Turin, Italy), and filtered by using a low-pass filter with a cut off frequency of 50-Hz. The MVT was calculated as the maximum of torque signal recorded during the two 3-s maximal voluntary contractions. The first derivative of the torque signal was computed to obtain the RTD signal ($Nm \cdot s^{-1}$, see Fig. 1b) and filtered using an overlapping moving window of 0.1 s (Boccia *et al.*, 2018b). If any countermovement was evident (i.e., a visible drop in torque), the contraction was rejected from the analysis. For each subject and all pulses, peak torque and peak RTD (which is local maximum of the RTD signal) were computed. $RTD_{maximal}$ was considered as the RTD recorded during the contraction presenting the highest RTD.

The linear regression parameters between peak torque and peak RTD (slope, R^2, y-intercept) were calculated for each participant. The Fig. 1c provides a representative example of linear regression. Outliers were detected and removed using the Cook distance methodology (Cook, 2000). The slope of linear regression (i.e., the RTD-SF) quantifying the ability to scale RTD with contraction amplitude was considered as the main outcome (Bellumori *et al.*, 2011; Mathern *et al.*, 2018). Secondary outcomes were the R^2 and the y-intercept.

Each linear relationship between peak torque and peak RTD was checked for the whole contraction range. As previously reported (Boccia *et al.*, 2018b; Casartelli *et al.*, 2014), some participants may not show a linear relationship across the whole contraction range. Rather, the relationship may be linear from 0 to about 70-90% of the maximal torque and then show a logarithmic behaviour from about 70-90% to the maximum. If a biphasic regression showed more variations between torque and RTD than a linear regression, the breakpoint for this interrupted regression was calculated and the coefficients for the first part of linear regression were considered (Linden, 2015). The average number of pulses to calculate the regression was 21±2 for quadriceps and 21±2 for hamstring.

Statistical analysis

To answer the first experimental question of the study, i.e. to assess the impact of RTD-SF and y-intercept, together with MVT, in predicting the $RTD_{maximal}$, we separately conducted hierarchical multiple regression analyses. We used $RTD_{maximal}$ as a dependent variable and MVT, RTD-SF and y-intercept as independent factors. Independent factors entered three steps, inside the regression model following this order: MVT in the Step 1, RTD-SF in the Step 2 and y-intercept in the Step 3. Moreover, as exploratory analysis, we investigated the relationship between RTD-SF and normalized $RTD_{maximal}$ ($RTD_{maximal}$/MVT) using Pearson correlation coefficient *r*.

To answer the second experimental question of the study, we estimated $RTD_{submaximal}$ at different torque levels using the linear regression calculated between RTD and peak torque (i.e., based on the slope and y-intercept of the RFD-SF). In this way we were able to obtain comparable results among subjects since it is unlikely to have isometric contractions with the same amplitude among subjects. Thus, we used the linear regression of the RTD-SF to estimate what would be the RTD for a specific level of peak torque. For example, to calculate the RTD in a ballistic contraction of 40 Nm amplitude we evaluated the linear regression $RTD = RTD\text{-}SF \cdot x + y\text{-}intercept$, using as *x* the value of 40 Nm. For each muscle group, we evaluated the RTD at approximately 20%, 40%, 60%, 80% of the average MVT. Specifically, for quadriceps we considered the following absolute values: 50 Nm (RTD_{50Nm}), 100 Nm (RTD_{100Nm}), 150 Nm (RTD_{150Nm}) and 200 Nm (RTD_{200Nm}). For hamstrings we considered the following values: 20 Nm (RTD_{20Nm}), 40 Nm (RTD_{40Nm}), 60 Nm (RTD_{60Nm}) and 80 Nm (RTD_{80Nm}).

Afterward, z-scores were computed for both $RTD_{maximal}$ and $RTD_{submaximal}$. Bland–Altman plots (1986) with 95% limits of agreement (i.e., mean difference ±1.96 SD) were determined to assess systematic variation between the data corresponding to z-score of

$RTD_{maximal}$ and $RTD_{submaximal}$. Using z-scores, which provide the value of an observation expressed in standard deviation units, we were able to compare the individual values measured under two different conditions (i.e., $RTD_{maximal}$ obtained with the classical method and the $RTD_{submaximal}$ obtained with RTD-SF protocol). In other words, the Bland-Altman plots inform about the difference between $RTD_{maximal}$ and $RTD_{submaximal}$ values expressed as standard deviation of the group distribution. As previously suggested (Rona *et al.*, 2011) we considered *wide* limits of agreement 2 z-scores or more, between 1.5–1.99 z-scores as *fairly wide*, and less than 1.5 z-scores as *reasonable agreement*. A Pearson product-moment correlation coefficient (r) was calculated between $RTD_{maximal}$ and $RTD_{submaximal}$. All the above analyses were separately performed for quadriceps and hamstrings.

Data are presented as mean ± standard deviation. The significance level was set at $p \leq 0.05$. The MATLAB R2017a (Mathworks, Natick, Massachusetts) was used for all statistical analyses.

Results

Table 1 displays the mean scores and SDs of recorded data (i.e., MVT, $RTD_{maximal}$, RTD-SF, R^2 and y-intercept) for both quadriceps and hamstrings. In 28 occasions out of 83 the relationship between peak torque and peak RTD was not linear for the whole contraction range and thus the coefficients for the linear part of regression were reported (i.e. up to 70-90% of maximal torque).

<Insert Table 1 about here>

Determinants of maximal RTD

Results of hierarchical multiple regression analyses for both quadriceps and hamstrings muscles are provided in Table 2. Briefly, in quadriceps in the Step 1 of the regression model MVT accounted for 60.0% of the variance in $RTD_{maximal.}$ The addition of RTD-SF (Step 2 of the regression model) accounted for 13.7% of the variance in $RTD_{maximal}$

while the addition of y-intercept (Step 3 of the regression model) accounted for 3.2% of the variance in $RTD_{maximal}$. MVT, RTD-SF and y-intercept accounted all together for 76.9 % of the variance in $RTD_{maximal}$ ($F_{3,37} = 41.026$, $p < 0.001$). In hamstrings, in the Step 1 of the regression model MVT accounted for 38.1% of the variance in $RTD_{maximal.}$ The addition of RTD-SF (Step 2 of the regression model) accounted for 18.7% of the variance in $RTD_{maximal}$ while the addition of y-intercept (Step 3 of the regression model) accounted for 4.5% of the variance in $RTD_{maximal}$. MVT, RTD-SF and y-intercept accounted all together for 61.2 % of the variance in $RTD_{maximal}$ ($F_{3,38} = 20.013$, $p < 0.001$).

<Insert Table 2 about here>

Correlation analysis showed a moderate relationship between RTD-SF and normalized $RTD_{maximal}$ in both quadriceps ($r = 0.62$, $p < 0.001$) and hamstrings ($r = 0.52$, $p < 0.001$).

Agreement between RTD in contractions of maximal and submaximal amplitude

Quadriceps The Figure 2 shows the Bland–Altman plots between the z-score of $RTD_{maximal}$ and $RTD_{submaximal}$ for quadriceps respectively. According to z-score calculations, the mean differences were centered (mean differences = 0 *z*-points). The limits of agreement were the following: ± 2.4 *z*-points between $RTD_{maximal}$ and RTD_{50Nm} (Fig. 2a); ± 2.1 *z*-points between $RTD_{maximal}$ and RTD_{100Nm} (Fig. 2b); ± 1.5 *z*-points between $RTD_{maximal}$ and RTD_{150Nm} (Fig. 2c); ± 0.9 *z*-points between $RTD_{maximal}$ and RTD_{200Nm} (Fig. 2d). The absolute values chosen for calculating the relative $RTD_{submaximal}$ were not reached by 8 and 20 subjects for RTD_{150Nm} and RTD_{200Nm} respectively. Thus it was not possible to determinate the data points in Bland–Altman plots for these subjects (see Fig. 2c and Fig. 2d).

$RTD_{maximal}$ was found to be correlated with RTD_{100Nm} ($r = 0.435$; $p = 0.004$), RTD_{150Nm} ($r = 0.729$; $p < 0.001$), RTD_{200Nm} ($r = 0.906$; $p < 0.001$), but not with RTD_{50Nm} ($r = 0.261$; $p = 0.098$).

<Insert Figure 2 about here>

Hamstrings The Figure 3 shows the Bland–Altman plots between the z-score of $RTD_{maximal}$ and $RTD_{submaximal}$ for hamstrings. According to z-score calculations, the mean differences were centered (mean differences = 0 *z*-points). The limits of agreement were the following: ± 2.7 *z*-points between $RTD_{maximal}$ and RTD_{20Nm} (Fig. 3a); ± 2.4 *z*-points between $RTD_{maximal}$ and RTD_{40Nm} (Fig. 3b); ± 2.2 *z*-points between $RTD_{maximal}$ and RTD_{60Nm} (Fig. 3c); ± 1.5 *z*-points between $RTD_{maximal}$ and RTD_{80Nm} (Fig. 3d). The absolute values chosen for calculating the relative $RTD_{submaximal}$ were not reached by 1 and 11 subjects for RTD_{60Nm} and RTD_{80Nm} respectively. Thus it was not possible to determine the data points in Bland–Altman plots for these subjects (see Fig. 3c and Fig. 3d).

$RTD_{maximal}$ was found to be correlated with RTD_{60Nm} ($r = 0.389$; $p = 0.012$) and RTD_{80Nm} ($r = 0.692$; $p < 0.001$), but not with RTD_{20Nm} ($r = 0.017$; $p = 0.913$) and RTD_{40Nm} ($r = 0.235$; $p = 0.133$).

<Insert Figure 3 about here>

Discussion

The aim of the study was to explore the relationship between the neuromuscular quickness in ballistic contractions of maximal compared to submaximal amplitudes. To do that, we measured the RTD in a series of ballistic contractions of either submaximal ($RTD_{submaximal}$) or maximal ($RTD_{maximal}$) amplitudes in both quadriceps and hamstrings of young soccer players. This allowed to determine the RTD-SF, which quantifies how much RTD scales with the amplitude of a ballistic contraction. We found that: 1) RTD-SF explained about the 14% and 19% of variance in $RTD_{maximal}$ in quadriceps and hamstrings, respectively; 2) the RTD achieved in ballistic contractions of submaximal amplitudes ($RTD_{submaximal}$) was weakly associated to $RTD_{maximal}$.

Determinants of maximal RTD

The ability to develop MVT and $RTD_{maximal}$ depends on partially different features of neuromuscular system (McGuigan *et al.*, 2010; Prebeg *et al.*, 2013). Broadly speaking, the RTD in first 50 ms strongly depends on the level of agonist activation (Maffiuletti *et al.*, 2016). Indeed, the muscle activation in the early phase of a ballistic contraction is usually suboptimal (on average 40% of maximum activation as measured through electromyography) and shows a large inter-subject variability (from 10 to 80%) (Folland *et al.*, 2014). Consequently, the capacity to rapidly increase muscle activation from the onset of the contraction is crucial to produce high RTD in the early phase of an explosive contraction. The fact that the neural factors profoundly influence the early phase of contraction may reside on the fact the motor units firing rate required to achieve maximal RTD are higher than those usually observed during a sustained maximal voluntary contraction (100-200 Hz vs 30-50 Hz) (Maffiuletti *et al.*, 2016; Rodríguez-Rosell *et al.*, 2017). Differently, the muscle contractile properties tend to be more associated with the late phase of RTD and with MVT (Folland *et al.*, 2014). For these reasons, while $RTD_{maximal}$ and MVT are closely linked (Andersen and Aagaard, 2006; Mirkov *et al.*, 2004), the between-subjects differences in MVT cannot fully explain the differences in $RTD_{maximal}$. For example, trained participants showed a two-fold absolute RTD compared with untrained participants, while showing only little differences (≈ 28%) in MVT (Tillin *et al.*, 2010). Regarding quadriceps, which is the most investigated muscle in this topic, herein findings show that MVT alone accounts for 60% of $RTD_{maximal}$ (Table 2), which is line with previous investigations (Andersen and Aagaard, 2006; Mirkov *et al.*, 2004). The novelty of this study is that, when adding the RTD-SF to the regression model, the variance explained increased by ≈14%. Regarding hamstrings, which is a muscle of increasing interest in the sports-related literature because of its proneness to injuries (Opar *et al.*, 2012), the trend was similar compared to quadriceps. Indeed, the inclusion of RTD-SF in the regression model to predict $RTD_{maximal}$, increased the explained variance accounted by ≈ 19%. These results suggest that RTD-SF may have a functional relevance in the relationship between MVT and $RTD_{maximal}$. Since RTD-SF quantifies the ability to scale the RTD with the amplitude of ballistic contraction (Freund and Budingen, 1978), it is therefore possible to speculate that RTD-SF influences the amount of torque that can be achievable in a quick muscle contraction.

Moreover, when the y-intercept of the RTD-SF regression was added to the model, the explained variance increased by 3 and 4%, in quadriceps and hamstrings, respectively. Even if this parameter is commonly neglected as a variable of interest (e.g., Bellumori et al., 2011; Djordjevic and Uygur, 2017; Haberland and Uygur, 2017) our results showed that the potentially shift upward or downward of the RTD-SF regression might affect the $RTD_{maximal}$.

In the exploratory part of this study, we found a moderate correlation between RTD-SF and normalized $RTD_{maximal}$. RTD-SF and normalized $RTD_{maximal}$ have in common that are features related to neuromuscular quickness and physiologically distinct from MVT. Even if this is outside the aims of this study, this is a novel result that deserves to be studied in future investigations.

Agreement between RTD in contractions of maximal and submaximal amplitude

To describe agreement between $RTD_{maximal}$ and $RTD_{submaximal}$ we evaluated the limits of agreement between the z-scores of each variable, provided by the Bland–Altman plots. We observed that the limits of agreement were wide when considering $RTD_{submaximal}$ in ballistic contraction of small amplitudes (e.g., 50 and 100 Nm in quadriceps and 20, 40 and 60 Nm in hamstrings, see Figure 2 and 3). Narrower, but still large, limits of agreement were observed between $RTD_{maximal}$ and $RTD_{submaximal}$ when targeting higher level of torque (e.g., 150 and 200 Nm in quadriceps and 80 Nm in hamstrings, see Figure 2 and 3). However, a number of subjects were not able to reach, in the ballistic contractions, the highest torque levels (i.e. 200

Nm for quadriceps and 80 Nm for hamstring) set to calculate the agreement between $RTD_{maximal}$ and $RTD_{submaximal}$ (see Fig 2d and 3d). This was because the highest torques were too close or even higher than the maximal torque of these participants. Consequently, the conclusions drawn for high torque levels should be taken more carefully.

The fact that the limits of agreement were overall wide means that the agreement between $RTD_{maximal}$ and $RTD_{submaximal}$ was poor. Thus, evaluating $RTD_{maximal}$ cannot be used as surrogate measure of $RTD_{submaximal}$ and vice-versa. Practically, to adopt ballistic contraction of sub-maximal amplitude ($RTD_{submaximal}$) may produce very different findings in RTD assessment, compared to ballistic contraction targeting (near-)maximal torque ($RTD_{maximal}$), as usually performed. The present finding allows to advocate the usefulness of evaluating the RTD when performing ballistic contractions across the whole range of torque levels, not only targeting maximal torques as usually performed. Since we suggested that the capacity to quickly produce submaximal torques could be as relevant as quickly produce maximal torque, we guess that adopting the herein protocol may be incorporated in the routine evaluation of neuromuscular quickness. Furthermore, since the association between $RTD_{maximal}$ and $RTD_{submaximal}$ was markedly weak when $RTD_{submaximal}$ was evaluated at low torque levels (e.g. lower than 50% of MVT), we speculate that this information could be even more important in context where the production of maximal torque is unlikely, e.g. ageing, injuries, daily life activities.

Limitations of the study

Some limitations should be underlined. First, this study involved young soccer players (range age 17-19) and the findings of this study may have been affected by biological maturations of the participants and thus should not be applied to different populations.

Moreover, the values of quadriceps RTD-SF found in this study (Table 1) were lower than those reported in previous studies (Bozic *et al.*, 2013; Bellumori *et al.*, 2011; Bellumori *et al.*, 2017). This underestimation in our results was likely to be caused by differences in dynamometers. Indeed, it has been suggested that the commercially available dynamometer adopted in this study tends to provide excessive compliance with respect to the custom-built dynamometers adopted in other studies. Even if we tried to minimize the compliance, this feature might have, at some extent, affected our results. Moreover, while 50 contractions were suggested to maximize the reliability of the RTD-SF (Bellumori *et al.*, 2011; Mathern *et al.*, 2018), we calculated the RTD-SF from fewer contractions (≈21) because of time constrains. Despite this, the consistency of the RTD-SF regression line was acceptably high (see Figure 1 for a representative example), indeed the R^2 obtained for both quadriceps and hamstring were ≈ 0.94.

Conclusions

The RTD scaling factor is a measure of the scaling of quickness with the magnitude of a contraction. Together with maximal voluntary torque, the RTD scaling factor was associated with the maximal RTD. This may suggest that the RTD scaling factor influences the amount of torque that can be achievable in a quick muscle contraction of maximal amplitude. Moreover, we suggest that estimating the RTD across the whole range of torque may provide additional meaningful information about the quickness capacity of quadriceps and hamstrings muscles. Indeed, our findings showed that the RTD recorded in ballistic contractions of either maximal or submaximal amplitude did not provide interchangeable results.

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Figure caption

Figure 1

Representative example of a set of ballistic contractions performed across a range of submaximal amplitudes during hamstrings contractions. A) Torque signals recorded during 5 or 6 ballistic contraction for each force level; B) RFD signals (first derivative of force); C) each point represents the peak RFD (y value) and the peak torque (x value) achieved in each ballistic contraction.

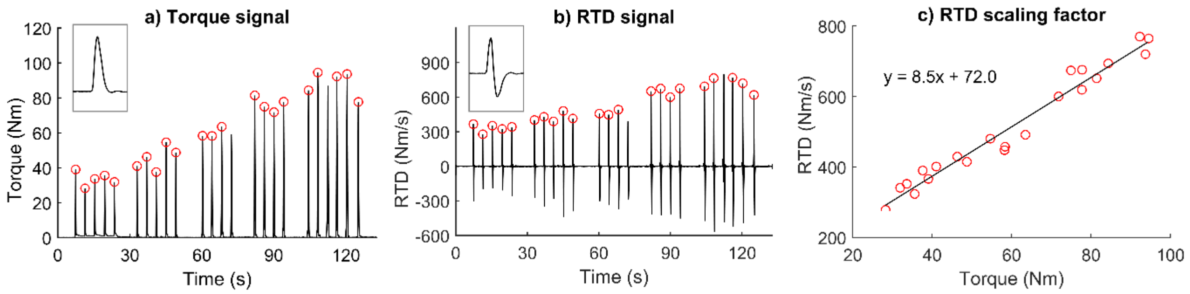

Figure 2

Bland-Altman plots of agreement between $RTD_{maximal}$ and RTD when targeting submaximal torques in quadriceps ($RTD_{submaximal}$). (a) RFD when targeting at 50 Nm (RTD_{50Nm}), (b) RFD when targeting at 100 Nm (RTD_{100Nm}), (c) RFD when targeting at 150 Nm (RTD_{150Nm}) and (d) RFD when targeting at 200 Nm (RTD_{200Nm}).

Solid lines represent mean bias differences; Dashed lines represent the limits of agreement (i.e., mean difference ± 1.96 SD).

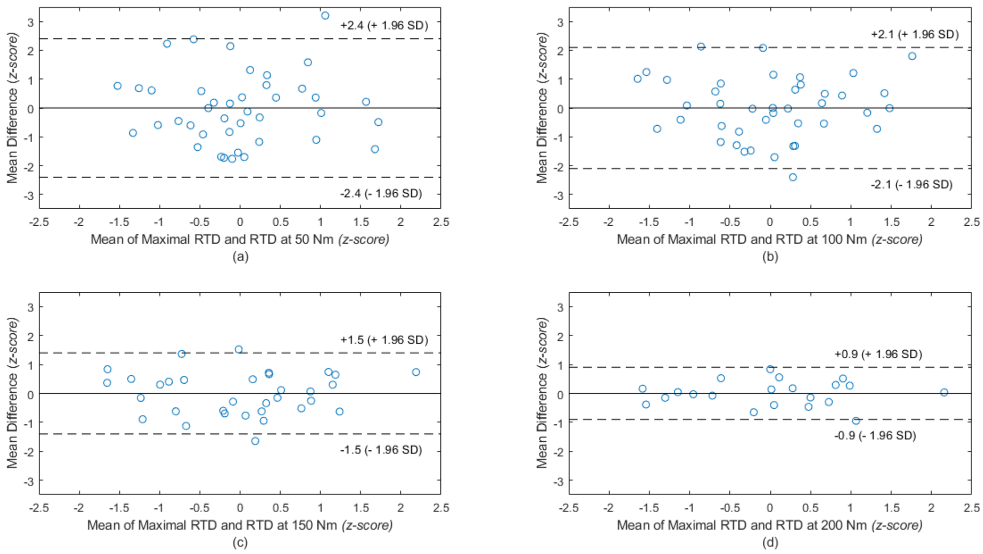

Figure 3

Bland-Altman plots of agreement between $RTD_{maximal}$ and RTD when targeting submaximal torques in hamstrings ($RTD_{submaximal}$). (a) RFD when targeting at 20 Nm (RTD_{20Nm}), (b) RTD when targeting at 40 Nm (RTD_{40Nm}), (c) RTD when targeting at 60 Nm (RTD_{60Nm}) and (d) RTD when targeting at 80 Nm (RTD_{80Nm}).

Solid lines represent mean bias differences; Dashed lines represent the limits of agreement (i.e., mean difference ± 1.96 SD).

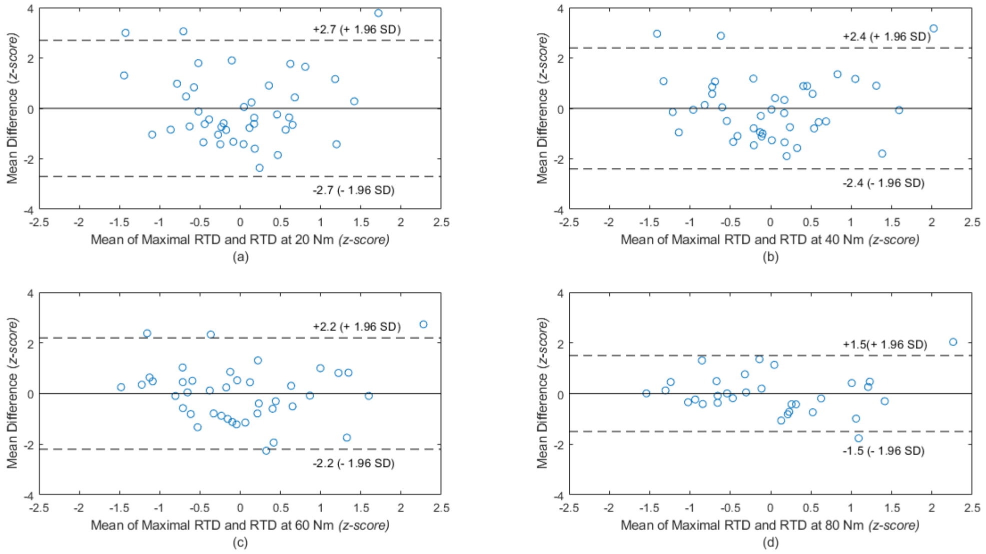

Table 1

Experimental results for both quadriceps and hamstrings.

	Quadriceps	Hamstrings
MVT (Nm)	251.6 ± 54.6	106.7 ± 23.0
$RTD_{maximal}$ ($Nm\ s^{-1}$)	1446.6 ± 322.4	830.2 ± 223.6
RTD-SF	6.9 ± 1.6	8.5 ± 1.6
y-intercept	193.9 ± 155.4	32.0 ± 92.0
R^2	0.94 ± 0.05	0.94 ± 0.04

Mean ± standard deviation. MVT, maximal voluntary torque; $RTD_{maximal}$, peak of rate of torque development; RTD-SF, rate of torque development scaling factor; y-intercept, intercept at y axis; R^2, R-squared of the regression.

Table 2 - *Summary of hierarchical regression analyses for both quadriceps and hamstrings.*

Measure	Independent variables	R^2	ΔR^2	β	*partial r*	*p*
Quadriceps						
$RTD_{maximal}$						
Step 1	MVT	0.600		0.775	0.775	<0.001
Step 2	MVT	0.737	0.137	0.784	0.837	<0.001
	RTD-SF			0.370	0.585	<0.001
Step 3	MVT	0.769	0.032	0.751	0.838	<0.001
	RTD-SF			0.508	0.641	<0.001
	y-intercept			0.228	0.347	0.031
Hamstrings						
$RTD_{maximal}$						
Step 1	MVT	0.381		0.617	0.617	<0.001
Step 2	MVT	0.567	0.187	0.587	0.665	<0.001
	RTD-SF			0.433	0.549	<0.001
Step 3	MVT	0.612	0.045	0.592	0.688	<0.001
	RTD-SF			0.611	0.601	<0.001
	y-intercept			0.278	0.323	0.042

Notes: R^2, proportion of variance accounted for variance in independent variables; ΔR^2, change in R^2; β, standardized regression coefficient; partial r, partial correlation controlling for the other independent variables; MVT, maximal voluntary torque; $RTD_{maximal}$, peak of rate of torque development; RTD-SF, rate of torque development scaling factor; y-intercept, intercept at y axis.