



Maximal vs. explosive knee extensor strength in professional soccer players: inter-limb asymmetries and relationship with knee function

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ABSTRACT

The main aims of this study were to compare the magnitude of inter-limb asymmetry (ILA) and the relation with self-reported knee function between maximal and explosive knee extensor strength outcomes in professional soccer players. Forty-six male soccer players completed different maximal isokinetic and isometric contractions of the knee extensors for the assessment of maximal strength (peak torque and maximal voluntary contraction (MVC) torque) and explosive strength (early, intermediate, late, and peak rate of torque development (RTD)). Self-reported knee function was assessed with the International Knee Documentation Committee (IKDC) and Lysholm knee scoring scales. Peak torque and MVC torque showed comparable ILAs (8–9%), both being significantly lower than all RTD ILAs (16% on average; $p < 0.001$). ILAs for early RTD (21%) and peak RTD (19%) were significantly higher than all the other variables ($p < 0.05$). Only early and intermediate RTD were significantly correlated – though weakly – with both IKDC ($\rho = 0.32$ for both) and Lysholm ($\rho = 0.36$ and 0.30 , respectively) scores. We conclude that explosive knee extensor strength – early RTD in particular – exhibited larger ILAs and better relations with self-reported knee function than peak torque and MVC torque in professional soccer players. These results confirm the validity and functional relevance of early RTD and the need for its inclusion in routine performance testing for soccer players.

Highlights

- Professional soccer players exhibited larger inter-limb deficits in knee extension strength for explosive actions than for the widely-used isokinetic test.
- Self-reported knee function was significantly correlated with explosive strength of the knee extensor muscles but not with maximal strength.
- The first 50 ms of an explosive knee extension seem to be crucial for self-perceived sport performance and possibly for injury prevention.

KEYWORDS

Isokinetic strength; rate of force development; dynamometry

Introduction

Knee extensor maximal strength – such as concentric peak torque obtained on an isokinetic dynamometer – is commonly included in pre-season period performance testing of professional soccer players. (Lehance et al., 2008) However, it has recently been suggested that explosive strength, i.e. the capacity to produce force/torque quickly during an explosive maximal voluntary contraction (MVC), is more representative of athletic performance as well as injury susceptibility (Padua et al., 2018; Suchomel et al., 2018; Zebis et al., 2011) and recovery (Jordan,

Aagaard, & Herzog, 2015; Nielsen et al., 2020) than pure maximal strength. (Buckthorpe & Roi, 2017; Maffiuletti et al., 2016) Nowadays, the main index of explosive strength is represented by the rate of torque development (RTD), which is generally calculated as the slope of the torque-time curve in distinct time intervals from contraction onset. (Maffiuletti et al., 2016) Accordingly, early RTD (≤ 100 ms) is usually distinguished from late RTD (≥ 200 ms), (Cossich & Maffiuletti, 2020; Maffiuletti et al., 2016) the former being mainly influenced by neural factors (e.g. motor unit behaviour) and the latter by muscular factors (e.g. muscle mass). (Cossich & Maffiuletti, 2020;

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Del Vecchio et al., 2019; Folland, Buckthorpe, & Hannah, 2014) An often used RTD variable is peak RTD, which corresponds to the highest rate of torque increase along the time-torque curve (steepest slope) that typically occurs between 30 and 100 ms from contraction onset. (D'Emanuele et al., 2021)

One of the simplest methods to compare strength data within and between subjects and methods consists in calculating the so-called inter-limb asymmetry (ILA), which expresses the relative difference of strength measures between the two limbs. (Impellizzeri et al., 2007) As such, an arbitrary threshold of $ILA \geq 10\%$ for isokinetic peak torque – which is considered to reflect a deficit in maximal strength – has been suggested to increase both muscular and ligament injury risk (Croisier et al., 2008; Grindem et al., 2016) in professional soccer players. (Croisier et al., 2008) Although maximal strength ILAs have widely been used for different purposes and in multiple conditions and populations, (Croisier et al., 2008; Ruas et al., 2015; Thomas et al., 2017) ILAs for explosive strength have received increasing attention only recently. (Angelozzi et al., 2012; Boccia et al., 2018; Markovic et al., 2020; Mirkov et al., 2017; Sarabon et al., 2020; Sarabon et al., 2020; Smajla et al., 2020; Smajla, Zitnik, & Sarabon, 2021; Turpeinen et al., 2020) Sarabon et al. (Sarabon et al., 2020) measured ILAs of 11% for knee extensor maximal strength vs. 18% for peak RTD in young healthy soccer players – suggestive of greater inter-limb deficits for explosive strength – but they did not test whether these differences were significant and only evaluated peak RTD. In another study conducted with professional soccer players, large ILAs (21–28%) persisted for various RTD variables but not for maximal strength 6 months after anterior cruciate ligament reconstruction, indicating a residual deficit of explosive strength despite full recovery of maximal strength and knee function. (Angelozzi et al., 2012) Although preliminary, these findings led us to conjecture that healthy professional soccer players may show inadequate RTD levels – possibly in relation with knee functional status – which could potentially affect physical performance (e.g. sprint velocity and vertical jump height) and increase the risk of injury (e.g. anterior cruciate ligament rupture).

Thus, in the present study we evaluated different isokinetic and isometric knee extensor strength variables in professional soccer players and compared the magnitude of ILAs and the relationship with self-reported knee function between maximal and explosive strength. The specific hypotheses were that RTD variables would disclose greater ILAs and stronger relationships with knee function than maximal strength.

Materials and methods

Subjects

A convenience sample of 46 male professional elite (premier Brazilian soccer league) soccer players from three different teams (mean age $\pm$ SD: 26 ± 6 yrs, body mass: 77 ± 9 kg, height: 180 ± 8 cm) volunteered to participate in this study. They were all playing in the highest Brazilian league and had practiced soccer on average for 15 ± 5 years. There were 5 goalkeepers (11%), 19 defenders (41%), 15 midfielders (33%), and 7 forwards (15%). The exclusion criteria were: history of lower limb or spine orthopedic surgery, any kind of pain precluding normal training (more than two consecutive training sessions lost in the last month), and any lower limb joint/muscle injury in the last 6 months, as verified with a self-reported survey. (Goes et al., 2020) The study was approved by the local ethics committee for human experiments and all participants provided written informed consent before participating.

Experimental protocol

All measurements were conducted during a single testing session lasting ~60 min that was scheduled during the pre-season (from November 2018 to February 2019). First, participants were asked to complete two questionnaires for the assessment of self-reported knee function. Then, they performed different series of maximal isokinetic and isometric contractions of the knee extensors for the assessment of maximal strength (concentric peak torque, isometric MVC torque) and explosive strength (various RTD variables). All measurements were conducted unilaterally on the left and right sides (presented randomly) and limbs were consistently classified as stronger (higher strength value) vs weaker (lower strength value).

Assessment of self-reported knee function

Self-reported knee function was assessed using the International Knee Documentation Committee (IKDC) subjective knee evaluation form (Irrgang et al., 2001) and the Lysholm knee scoring scale. (Lysholm & Gillquist, 1982) Both questionnaires evaluate knee functional status with a total score ranging from 0 to 100 (the higher the better) encompassing symptoms (pain, stiffness, etc.), sports and daily activities, as well as current knee function. For both questionnaires, the cross-culturally adapted and validated Portuguese version was used. (Irrgang et al., 2010; Peccin, Ciconelli, & Cohen, 2006)

Assessment of maximal and explosive strength

Maximal and explosive knee extensor strength were assessed using an isokinetic dynamometer (Humac Norm II, CSMI, USA) with continuously-provided real-time visual feedback of the torque signal. Participants were seated with both hips at $\sim 90^\circ$, the trunk stabilised by seat belts, and the tested knee aligned with the dynamometer rotational axis. First, they performed a warm-up/familiarisation set of five progressive (20, 40, 60, 80, and 100% of maximal perceived effort) concentric knee extensions with an angular velocity of $60^\circ/\text{s}$ and a range of motion of 90° (0° = full extension). Then, they completed five consecutive maximal trials with strong verbal encouragement, from which the highest concentric peak torque (hereafter referred to as peak torque) and the corresponding angle of peak torque were retained. The individually-obtained angle of peak torque (mean $\pm$ SD: $68 \pm 10^\circ$) was employed for the subsequent explosive isometric contractions. (Laett et al., 2021) After 5 min of rest, the dynamometer was set in isometric mode, and participants were asked to complete a standardised familiarisation procedure to learn how to execute the explosive actions while avoiding a countermovement. (Cossich & Maffiuletti, 2020; Laett et al., 2021) Then, they performed three explosive MVC of ~ 3 s, interspersed by rest periods of 30 s, from which MVC torque and different RTD variables were quantified (see below). Subjects were consistently instructed to produce force “as fast and hard as possible” during the explosive MVC and to keep the maximum effort as long as requested by the examiner. To minimise the dampening effect occurring at the interface between the shin and the dynamometer, and also to avoid pain, a standard soccer hard shin guard was used. (Laett et al., 2021)

The torque signal provided by the dynamometer was sampled at 1 kHz using an external A/D converter (EMG 830c®, EMG System do Brasil, São José dos Campos, SP, Brazil) and data were processed by a custom-built software developed in Matlab (Mathworks Inc., Natick, MA, USA). The torque signal was low-pass filtered using a fourth-order, 50 Hz cut-off frequency, zero-lag Butterworth filter. (Cossich & Maffiuletti, 2020) Contraction onset was defined by a fixed torque threshold of 1 Nm and was visually determined by the same experimenter. (Cossich & Maffiuletti, 2020) The torque signal was corrected for the passive torque using the average torque produced during a baseline resting period of 500 ms. MVC torque was quantified as the highest single-point torque value recorded throughout the explosive contractions (test-retest CV: 7.1%, ICC: 0.89 – as measured from a group of healthy men – see the supplementary

material (Supplementary 1) for a detailed description of additional reliability analyses). RTD was calculated as the slope of the torque-time trace at intervals of 50 ms (RTD_{50} – CV: 27.6%, ICC: 0.71), 150 ms (RTD_{150} – CV: 10.9%, ICC: 0.87), and 250 ms (RTD_{250} – CV: 8.9%, ICC: 0.89) from contraction onset, (Maffiuletti et al., 2016) representing respectively early, intermediate, and late RTD. Additionally, peak RTD (CV: 9.6%, ICC: 0.87) was obtained as the maximal positive value from the discrete derivative of the torque-time signal. (Maffiuletti et al., 2016) Only the trial with the highest MVC torque was used for all the analyses.

For all maximal (peak torque, MVC torque) and explosive strength variables (RTD_{50} , RTD_{150} , RTD_{250} , peak RTD), ILA was calculated according to equation 1. (Bishop et al., 2021) An ILA value $\geq 10\%$ was arbitrarily considered as a “strength deficit”, (Bishop et al., 2021; Thomas et al., 2017) and for each variable the proportion of subjects with an arbitrarily-defined strength deficit was calculated.

$$\text{ILA (\%)} = \left(\frac{\text{stronger limb(left or right)} - \text{weaker limb(left or right)}}{\text{stronger limb(left or right)}} \right) \times 100 \quad (1)$$

Statistical analysis

Absolute strength data – but not ILAs and questionnaire scores – were normally distributed (Shapiro–Wilk test). For all maximal and explosive strength outcomes, differences between limbs (stronger vs. weaker) were verified using paired t-tests, and effect sizes were measured using Cohen’s d. Effect sizes were classified as small (<0.20), medium (0.5), large (0.8) and very large (1.3). (Sullivan & Feinn, 2012) For ILAs, differences among strength outcomes were verified using a non-parametric Friedman’s ANOVA, followed by a Wilcoxon test for pairwise follow-up analyses. Also, we identified the stronger limb (right or left) and verified if the stronger limb was also the dominant one as a Boolean variable (Was the stronger limb the dominant one? True or False). We then used the Cohen’s kappa coefficient (κ) to measure the degree of agreement between strength measures using the Boolean variable. This approach was used to understand if the same limb always outperformed the other limb (i.e. the same limb was stronger across all measures, as reflected by a higher κ). The κ coefficients were classified as poor (<0.0), slight (0.0–0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80), and almost perfect (0.81–1.00). (Rau et al., 2011) The relationships between strength outcomes (stronger side, strength relative to body weight) and self-reported knee function (IKDC and Lysholm scores) were evaluated

Table 1. Maximal and explosive strength of the stronger and weaker limb, with respective ILAs.

	Stronger limb	Weaker limb	Effect size [95%CI]	ILA (%)	Subjects with strength deficit
Maximal strength					
Peak torque (Nm)	262 ± 43*	238 ± 44	0.54 [0.13, 0.96]	9.0 ± 7.1	19 (41%)
MVC torque (Nm)	335 ± 52*	307 ± 52	0.54 [0.12, 0.96]	8.4 ± 6.6	18 (39%)
Explosive strength					
RTD ₅₀ (Nm/s)	2652 ± 729*	2120 ± 739	0.73 [0.3, 1.15]	20.6 ± 14.3	31 (67%)
RTD ₁₅₀ (Nm/s)	1680 ± 336*	1444 ± 340	0.70 [0.28, 1.12]	14.0 ± 10.2	27 (59%)
RTD ₂₅₀ (Nm/s)	1178 ± 227*	1033 ± 230	0.64 [0.22, 1.05]	12.3 ± 9.9	23 (50%)
Peak RTD (Nm/s)	3708 ± 1004*	3024 ± 946	0.70 [0.28, 1.12]	18.7 ± 11.1	34 (74%)

Mean values ± SD. CI, confidence interval; ILA, inter-limb asymmetry; MVC, maximal voluntary contraction; RTD, rate of torque development *Significantly higher than weaker limb ($p < 0.001$).

using Spearman rank-order correlation coefficients (ρ). Correlation coefficients were classified as negligible (<0.19), weak (0.20–0.39), moderate (0.40–0.59), and strong (0.60–0.89). (Schober, Boer, & Schwarte, 2018) The threshold for statistical significance was set to $p < 0.05$ for all the analyses. All statistical procedures and image plotting were performed by a custom-made Python 3.0 routine.

Results

There were significant differences between the stronger and weaker limbs for all strength outcomes ($p < 0.001$), with effect sizes ranging from 0.54 (peak torque and MVC torque) to 0.73 (RTD₅₀) (Table 1).

Mean ILAs were comparable for peak torque and MVC torque ($p = 0.88$), both being significantly lower than all RTD ILAs ($p < 0.001$; Table 1 and Figure 1). Likewise, ILAs were not significantly different between RTD₁₅₀ and RTD₂₅₀ ($p = 0.13$), but both were significantly lower than RTD₅₀ ($p = 0.01$) and peak RTD ($p < 0.01$). ILAs did not differ significantly between RTD₅₀ and peak RTD ($p = 0.57$). The proportion of subjects with an arbitrarily-defined strength deficit (ILA $\geq 10\%$) was lower for maximal strength (40% on average) than for explosive strength outcomes (62% on average), the highest proportion being observed for RTD₅₀ and peak RTD (70% on average; Table 1 and Figure 1).

The dominant limb was the right for 67.4% of the players. Percentage values of correspondence between the dominant limb and the stronger limb were: peak torque (Yes: 56.5%, No: 43.5%), MVC torque (Yes: 52.2%, No: 47.8%), RTD₅₀ (Yes: 54.4%, No: 45.7%), RTD₁₅₀ (Yes: 56.5%, No: 43.5%), RTD₂₅₀ (Yes: 52.2%, No: 47.8%), and Peak RTD (Yes: 67.4%, No: 32.6%). We observed moderate agreement between maximal

strength variables (peak torque–MVC torque, $\kappa = 0.57$ – Figure 2), while the remaining coefficients were classified as poor, slight, or fair (Figure 2).

The observed IKDC and Lysholm scores were 97 (4) and 84 (3), respectively (median and interquartile range). Peak torque and MVC torque did not correlate significantly with neither IKDC ($\rho = 0.16$ and 0.08, respectively; $p > 0.05$) nor Lysholm scores ($\rho = 0.08$ and 0.19, respectively; $p > 0.05$). A weak positive correlation was found between RTD₅₀ and both IKDC ($\rho = 0.32$; $p = 0.02$) and Lysholm scores ($\rho = 0.36$; $p = 0.01$; Figure 3). A weak positive correlation was also observed between RTD₁₅₀ and both IKDC ($\rho = 0.32$; $p = 0.03$) and Lysholm scores ($\rho = 0.30$; $p = 0.04$). RTD₂₅₀ and peak RTD did not correlate significantly with neither IKDC ($\rho = 0.24$ and 0.18, respectively; $p > 0.05$) nor Lysholm scores ($\rho = 0.20$ and 0.28, respectively; $p > 0.05$).

Discussion

The main findings of this study were that (1) the magnitude of ILAs and the proportion of subjects with an objective though arbitrarily-defined inter-limb strength deficit were significantly greater for explosive than for maximal strength outcomes, and more particularly so for RTD₅₀ and peak RTD; (2) explosive strength measures were better related to self-reported knee function than maximal strength, and more particularly so for RTD₅₀ and RTD₁₅₀.

The present study demonstrated mean ILAs ranging from 8–9% (isokinetic peak torque and MVC torque) to 19–21% (peak RTD and RTD₅₀), which are very similar to those previously reported in young soccer players (11% for MVC torque and 18% for peak RTD), (Sarabon et al., 2020) but also in a large group of semi-professional athletes of different age, sex, and sport (10% for MVC

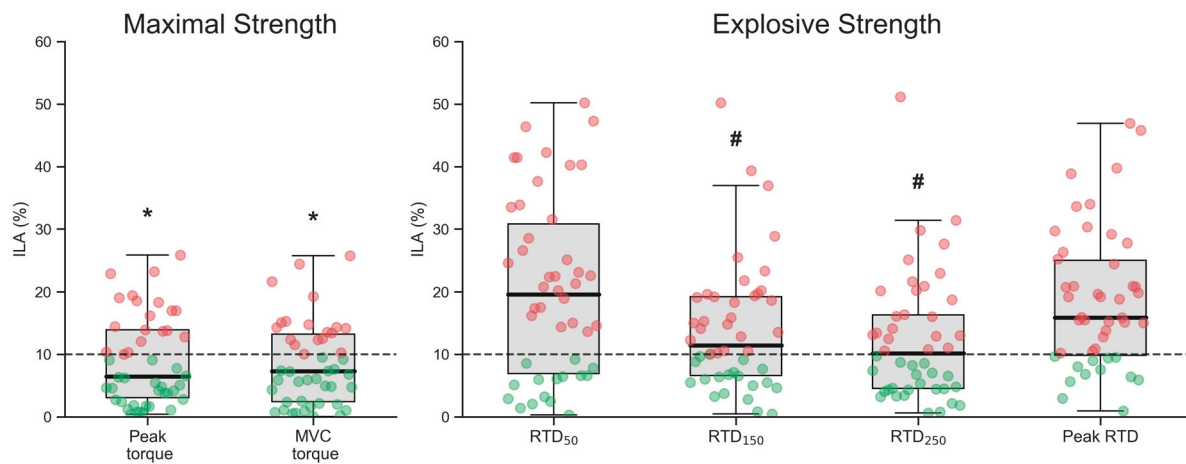


Figure 1. Inter-limb asymmetries (ILAs) for the different maximal and explosive strength outcomes (green and red dots represent ILAs below and above the 10% threshold, respectively). The median (bold line) and interquartile range (whiskers) are displayed as boxplots. *Significantly lower than all RTD ILAs ($p < 0.001$). #Significantly lower than RTD₅₀ and peak RTD ILAs ($p < 0.05$).

torque, 20% for peak RTD). (Sarabon et al., 2020) Thus, it seems that these findings of an approximately double ILA for explosive vs. maximal strength are not specific to healthy professional soccer players. Interestingly, ILAs for different RTD variables were even higher (21–28%) in professional soccer players when examined 6 months after ACL reconstruction, (Angelozzi et al., 2012) at a time when ILA for maximal strength was close to zero. These findings lend further support to

the ecological validity of RTD, although their study employed a multi-joint task that involved mainly, but not only, the knee extensor muscles (lower limb extension on a leg press). In agreement with Sarabon et al., (Sarabon et al., 2020) we noted that ILAs decreased progressively with increasing RTD time interval, so that the largest ILAs were systematically observed for RTD₅₀ in both studies. One possible explanation for these results is the large contribution of neural factors (such as motor unit behaviour) during the very early phase of an explosive contraction, (Cossich & Maffiuletti, 2020; Del Vecchio et al., 2019; Folland et al., 2014) which progressively declines as a result of an increased contribution of muscular factors at later stages (≥ 200 ms) (Folland et al., 2014). Accordingly, the present findings of greater strength deficits for early than for late RTD may be speculatively considered to be of neural origin, which is indirectly supported by the lower kappa coefficients (higher dominance fluctuations between early RTD and maximal strength).

In our present study, ILAs were also used to categorise subjects as having or not having a strength deficit using the classical – though arbitrary – 10% threshold, (Impellizzeri et al., 2007) which corresponds to the benchmark widely adopted for decision making (e.g. return to sport) in clinical practice. (Grindem et al., 2016) When considering maximal strength, the mean proportion of subjects with an arbitrarily-defined strength deficit was on average 40% vs 70% for RTD₅₀ and peak RTD. These results, taken together with those of Angelozzi et al., (Angelozzi et al., 2012) seem to confirm that both the magnitude of ILAs and the prevalence of abnormal ILAs for maximal strength (including the widely-used isokinetic peak torque) do not reflect the actual strength deficits that are in fact largely

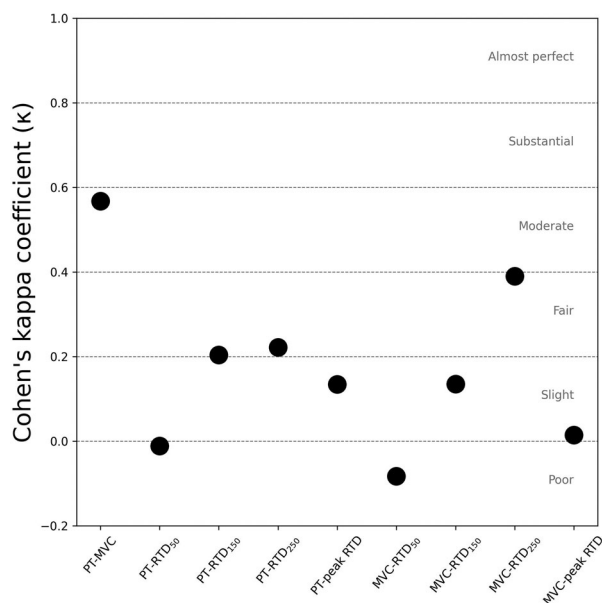


Figure 2. Cohen's kappa agreement coefficients to assess the correspondence between the dominant and the stronger limbs for pairs of strength variables. Notice that a higher kappa coefficient indicates a higher agreement between the variables regarding the question: was the stronger limb the dominant one? In other words, the same limb was stronger across the measures.

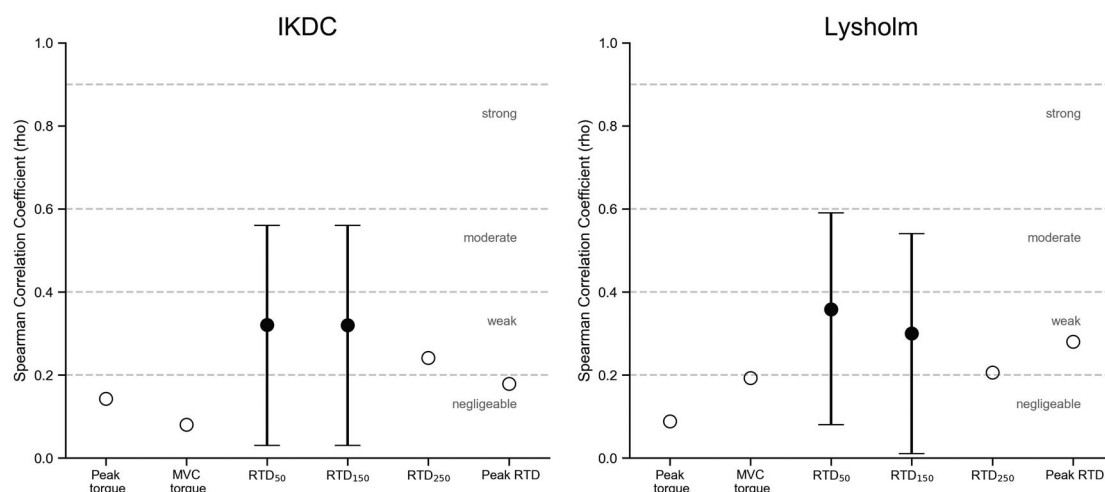


Figure 3. Spearman correlation coefficients between IKDC (left panel) or Lysholm scores (right panel) and the different maximal and explosive strength outcomes. White circles represent non-significant correlations. Black circles represent significant correlations with 95% confidence intervals (error bars). Correlation benchmarks are also shown as horizontal dashed lines.

underestimated with respect to early/peak RTD. It should be highlighted that the significant differences amongst the ILAs observed here (maximal vs. explosive strength and early vs. late RTD) do not merely reflect a poor between-day variability in MVC torque and RTD as supported by the additional reliability analyses (please see Supplementary 1), thereby reinforcing the relevance of the present results. Thus, because the exclusive consideration of maximal strength could contribute to underestimate the true strength deficits and in turn result in unsafe decisions, the evaluation of explosive strength – early RTD in particular – is warranted.

Although the present results are interesting, it should be kept in mind that we used an arbitrarily-defined, however widely used threshold, for “strength deficit” classification. The “10% rule” is flawed by concept as suggested by Bishop (Bishop, 2021), who proposed a new approach considering the individual variability of ILA to certify a “true asymmetry”. Unfortunately, we were unable to measure such individual variability due to the lack of athletes’ availability for further evaluations. Thus, we suggest that the 10% threshold used here should be treated as guidance but not as a closed concept to classify strength deficits. Future studies should calculate the strength asymmetry inter-subject variance for a better understanding of true asymmetries in professional soccer players.

In agreement with previous investigations conducted in subjects with knee injuries, (Angelozzi et al., 2012; Hirschmüller et al., 2017; Hsieh et al., 2014) we did not find significant correlations between maximal knee extensor strength and self-reported knee function. As far as explosive strength is concerned, the correlation between RTD and IKDC score has previously been

found to be negligible and not significant in professional soccer players (Angelozzi et al., 2012) while it was significant in active subjects (Hsieh et al., 2014) following anterior cruciate ligament reconstruction. Our results expand these observations demonstrating a significant albeit weak association between self-reported knee function scores (both IKDC and Lysholm) and early/intermediate RTD in healthy professional soccer players. Taken as a whole, these results confirm the superior functional relevance of assessing early RTD against pure maximal strength, as in fact the capacity to produce torque quickly is regarded as fundamental to sport-related performance and, possibly, protection against injury. (Buckthorpe & Roi, 2017; Maffiuletti et al., 2016)

The present results have important implications for practitioners seeking to improve knee extensor explosive strength and to reduce the associated ILAs in professional soccer players. As a recommendation, the evaluation of early and/or peak RTD of the knee extensors could be included in routine performance testing with the goals to monitor seasonal changes in explosive strength (i.e. for evaluative purposes) and/or to detect inter-limb strength deficits on an individual basis for diagnostic (e.g. presence of muscle weakness) or predictive purposes (e.g. increased risk of injury). The procedure – described in detail elsewhere (Maffiuletti et al., 2016) – only requires a relatively inexpensive and portable dynamometer, a short test session (~10 min per athlete, warm up included) and a few methodological requirements (Maffiuletti et al., 2016) to provide a potentially valuable ILA score. As discussed above and elsewhere, (Angelozzi et al., 2012) the classical isokinetic evaluation based on peak torque may not guarantee the

absence of a lingering and functionally harmful deficit of explosive strength and may therefore not stand alone.

A limitation of our study is that maximal and explosive strength were only evaluated for the knee extensor muscles, which have a well-recognized functional and preventive role in soccer, but not for muscle groups with a greater risk of traumatic and overuse injury in professional male soccer, such as hamstring or adductor muscles. (Croisier et al., 2008; Ekstrand, Häggglund, & Waldén, 2011) Also, we did not collect strength data from recently-injured soccer players, female or younger players, so that the interpretation of the current findings should not be extended beyond healthy male professional soccer players.

Conclusion

Explosive knee extensor strength, quantified as the RTD measured at different intervals from contraction onset – early RTD in particular – exhibited larger ILAs and stronger relationships with self-reported knee function than maximal strength (peak torque and MVC torque) in professional soccer players. These results confirm the validity and functional relevance of early RTD assessment and the need for its inclusion in routine performance testing for soccer players.

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