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The influence of angle-specific torque of the knee flexors and extensors on the angle-specific dynamic control ratio in professional female soccer players

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ABSTRACT

The purpose of this study was to assess whether dynamic torque ratios (DCR) from isokinetic strength assessments of eccentric knee flexors (eccKF) and concentric knee extensors (conKE) display differences when stratified into specific angle-specific DCR (DCR_{AST}) groups. Fifty-two professional female soccer players (age 21.30 ± 4.44 years; height 166.56 ± 5.17 cm; mass 61.55 ± 5.73 kg) from the English Women's Super League completed strength assessments of both lower limbs on an isokinetic dynamometer at 60° $\cdot s^{-1}$. Angle-specific torque (AST) were used to calculate DCR_{AST} to create sub-groups using clustering algorithms. The results identified for the dominant side that the Medium DCR_{AST} group elicited significantly higher conKE AST when compared to Low and High DCR_{AST} groups at increased knee extension ($P \leq 0.05$). For the non-dominant side, the High DCR_{AST} group had significantly higher and lower eccKF and conKE AST compared to the Low DCR_{AST} group at increased knee extension ($P \leq 0.05$). This study highlights that the inclusion of AST data may subsequently help practitioners to prescribe exercise that promotes strength increases at targeted joint angles. In turn, these approaches can be used to help reduce injury risk, identify rehabilitation responses and help inform return to play.

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KEYWORDS
Female soccer; dynamic control ratio; angle-specific torque; knee extensors; knee flexors

Introduction

Isokinetic dynamometry (IKD) is considered the "gold standard" of strength assessments and has been used by practitioners in professional soccer to quantify the strength of the thigh musculature. Higher conKE strength has demonstrated relationships with superior jump and sprint performance (Hägglund and Waldén, 2015; Montalvo et al., 2019). Higher eccKF strength has also been associated with improved sprint performance due to the increased ability of the musculature to store and release kinetic energy (Siddle et al., 2019; Suarez-Arrones et al., 2019). However, the association between eccKF and conKE strength and dynamic control (DCR), defined as the ratio of eccKF:conKE peak torque, has yielded equivocal findings (Croisier et al., 2008; Lee et al., 2018; Van Dyk et al., 2017). The ambiguity is attributed to injured partiicipants displaying similar peak torques compared to non-injured (Van Dyk et al., 2016), and several other factors (Hewett & Myer, 2011) in particular, peak torque and its inability to determine performance across the entire torque-angle curve (Eustace et al., 2017; De Ste Croix et al., 2017). An approach examining angle-specific torques is likely to be more robust; however, evidence is sparse (Eustace et al., 2017, 2019, 2020). Although it is not possible to measure isokinetic torque at full knee extension (≤ 20°) due to the presence of acceleration, quantifying strength at a limited range in 10° increments (70–40°) may limit this approach (Cohen et al., 2015; De Ste Croix et al., 2017). This reiterates a need to report torques at precise joint angles that inform interpretation for practitioners, with implications for performance and injury, particularly in females who are at an increased risk of thigh musculature and knee ligament injuries (Hägglund and Waldén, 2016; Montalvo et al., 2019).

The risk of thigh musculature and knee ligament injuries are also associated with strength imbalances between the eccKF and conKE that display low DCR's (Fritsch et al., 2020; Van Dyk et al., 2016, p. 2017). An optimal DCR has been identified as 1, indicating equal strength of the eccKF and conKE (Aagaard et al., 1998; Lee et al., 2018). Further evidence highlights that increased DCR's are indicative of a reduced injury risk to the knee flexors and knee ligaments as a result of decreased anterior shear forces exhibited at the knee joint (Doorenbosch & Harlaar, 2003; Kellis et al., 2003). However, the corresponding torque value must, however, also be considered as a DCR of 1 could be misleading to practitioners if both the eccKF and conKE have equal strength impairments. As such, this may attribute to the inability of the DCR to predict injury and stratify individuals with different injury risks. Moreover, the peak torques of the eccKF and conKE occur at different knee joint angles (Eustace et al., 2017; De Ste Croix et al., 2017); as such torque is effected by muscle length, limiting the clinical relevance of this metric. The DCR should also be calculated at specific knee joint angles to identify where the largest muscle imbalances exist across an angular range, particularly at extended knee joint angles where injury to the knee flexors and knee ligaments are more likely to occur (Croisier et al., 2008; Della Villa et al., 2020; Hewett & Myer, 2011; Lee et al., 2018; Lucarno et al., 2021).

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Previous observations have identified that higher peak torques of the conKE relative to the eccKF are indicative of a higher DCR in professional male soccer players (Fritsch et al., 2020), this has yet to be conducted across an angular range. Identifying angle-specific torques (AST) and DCR may highlight increased imbalances at precise joint angles. In turn, can inform practitioners to adopt training interventions that promote strengthening in a specific range of motion (Barak et al., 2004). Therefore, the purpose of this study was to assess whether angle-specific DCR (DCR_{AST}) from isokinetic strength assessments of eccKF and conKE in professional female soccer players display differences when stratified into specific angle-specific DCR (DCR_{AST}) groups. The present study aimed to identify whether female soccer players with higher or lower DCRAST values would exhibit differences in eccKF and conKE AST for dominant and non-dominant lower limbs. It was hypothesised that those with higher DCRAST would exhibit higher eccKF and lower conKE AST than those with lower DCR_{AST}.

Material and methods

Following ethics approval and written informed consent, fifty-two professional female soccer players (age 21.30 ± 4.44 years; height 166.56 ± 5.17 cm; mass 61.55 ± 5.73 kg) belonging to the Women's Super League in England participated in the study. All players were free from lower limb injury for 3 months at the time of testing. In addition to weekly matches, player's training volumes were >10 hr·week^{-1}. Prior to the commencement of the study, all participants completed a health, physical activity, pre-exercise control questionnaire.

During pre-season, participants attended the laboratory on two occasions to complete a familiarisation trial and an experimental trial. Each visit was separated by a minimum of 96 hr. The procedures of the familiarisation trial replicated the experimental condition. To control for circadian variation (Rae et al., 2015), testing was conducted in accordance with the player's regular training times. Participants attended the laboratory in a 3 hr post-absorptive state following a 48 hr abstinence from exercise, where height and mass were determined. As previous observations have identified that isokinetic strength measures of the thigh musculature are consistent across different phases of the menstrual cycle (Gordon et al., 2013; Gür et al., 1999) the current study therefore did not control for menstruation. Prior to the start of each trial, participants were required to complete a standardised 5-minute warm-up on a stationary cycle ergometer (Monark, 824E, Sweden) at 60 W.

The experimental trial comprised the completion of bilateral isokinetic (System 4, Biodex Medical Systems, Shirley, New York, USA) strength assessments of eccKF and conKE at 60°·s^{-1}, where participants were instructed to elicit 3 submaximal attempts, followed by 5 maximal contractions in accordance with previous procedures (Eustace et al., 2017). The dominant limb was defined as the preferred kicking limb (Greig, 2008). Strength assessments of both lower limbs were conducted as thigh musculature strains and knee ligament injuries are suggested to more likely occur at the dominant and non-dominant limbs, respectively (Le Gall et al., 2008; Hägglund & Waldén, 2016). Previous observations in isokinetic strength assessments of the thigh musculature identified acceptable reliability for conKE and eccKF at 60°·s^{-1} in professional female soccer players (Eustace et al., 2019). No performance feedback or instructions were provided during the experimental procedures due to reported effects on isokinetic torque (Campenella et al., 2000) and equivocal results when providing internal and external instructions during isokinetic strength assessments (Marchant & Greig, 2017; Marchant et al., 2009). The range of motion (ROM) of the knee joint was set at 25–90° (0° = full extension), and gravity corrected at 25° of knee flexion in accordance with the manufacturer's guidelines. The anatomical reference set at 90° of knee flexion. Participants was secured in a seated position with approximately 90° hip flexion, with restraints applied proximal to the knee joint, thigh, waist and chest. The lever arm alignment to the lateral femoral epicondyle was conducted in a position between knee extension and flexion to account for potential misalignment that can occur during the completion of the exercise.

The isokinetic phase of each repetition (sampled at 100 Hz) was analysed, and the repetition eliciting the highest gravity-corrected torque was subject to further analysis. Torque data were initially smoothed using a Low pass second-order Butterworth filter with a cut-off frequency of 5 Hz using a customised script in RStudio (Version 4.0.4, Boston, US). The isokinetic phase was then identified at the constant angular velocity by applying a 1% cut-off in Microsoft Excel. Data were expressed as absolute and relative to body mass for PT and AST. The eccKF and conKE AST were identified at each angle across a consistent angular range between 80° and 30°, and subsequently calculated the DCR^{AST} for both lower limbs.

Clustering of DCR_{AST} was performed using a trajectory-based longitudinal clustering algorithm implemented utilising the kml-shape package in RStudio in accordance with current guidelines (Genolini et al., 2016). Longitudinal clustering enables the identification of sub-groups based on the magnitude and shape of trajectories. Data were initially scaled, so the partitioning of the trajectories was computed with equal weighting of the vertical and horizontal axes to partition those with different curves. Thereafter, the Fréchet distance is determined using randomly selected individual trajectories. The Fréchet distance is a point of a trajectory linked to the nearest part on another trajectory. Subsequently, the Fréchet distance is the longest link between the two trajectories. As the vertical and horizontal axes differed in units of measurements, the generalised Fréchet distance was used to account for influencing distances between trajectories. The Fréchet mean is subsequently determined to construct the centres of the different trajectories for each respective cluster identified. The number of cluster groups, number of observations and Fréchet means cluster centres are summarised in Table 1 for each lower limb. The corresponding conKE and eccKF AST data were then subject to statistical comparisons between groups.

To identify absolute and relative differences in conKE and eccKF AST between different DCR_{AST} groups, as identified by longitudinal clustering, independent t-tests (non-dominant limb) and one-way ANOVA (dominant limb) were performed. Normality of all dependent variables were determined prior to statistical treatment (P > 0.05). Group differences were determined in MATLAB (R2019a, version 9.6.0.1072779, The MathWorks, Inc.,

Table 1. Identifies the number of observations and clusters identified for longitudinal cluster analysis.

	High Group	Medium Group	Low Group
Dominant limb DCR_{AST}: Number of observations in each cluster	7	26	19
Dominant limb DCR_{AST}: Fréchet mean (au)	0.05	0.04	0.03
Non-dominant limb DCR_{AST}: Number of observations in each cluster	25	-	27
Non-dominant limb DCR_{AST}: Fréchet mean (au)	0.05	-	0.03

Angle-specific dynamic control ratio (DCR_{AST})

Natick, US) and implemented using the open-source one-dimensional SPM code (spm1D-package, version 0.4.3, http://spm1d.org/index.html). If SPM{t/f} crossed the critical threshold, a supra- or infra-threshold cluster depicted by grey shading indicated a significant difference ($P \leq 0.05$) between groups at a specific phase in the torque-angle curve. Where significant main effects were observed for one-way ANOVA, post hoc pairwise comparisons were conducted. To estimate effect sizes, Cohens D (d) were calculated and classified as no effect (0 to 0.19), small (0.2 170 to 0.49), Medium (0.5 to 0.79) and large (≥ 0.8) (Cohen, 1988). Partial eta squared (η^2) values were also calculated to estimate effect sizes for all significant main effects and interactions for one-way ANOVA. Partial eta squared was classified as small (0.01 to 0.059), moderate (0.06 to 0.137) and large (>0.138) (Cohen, 1988). Graphical presentation of the torque-angle curves were performed using GraphPad Prism (Version 8.3.1, San Diego, US). Data are presented as means with standard deviations. Statistical significance was set at $P \leq 0.05$.

Results

As illustrated by Figure 1 for the dominant limb, one-way ANOVA identified a significant main effect for AST conKE across DCR_{AST} groups (Low, Medium and High) ($P < 0.001$; $\eta^2 = 0.094$). Post hoc analysis in panel 1B revealed no significant differences in the torque-angle curve between High and Low DCR_{AST} groups ($P > 0.05$). However, in panel 1C, the Medium DCR_{AST} group was significantly higher than the High DCR_{AST} group between 64° and 30° of knee flexion ($P < 0.001$). In panel 1D the Medium DCR_{AST} group was significantly higher than the Low DCR_{AST} group between 48° and 30° of knee flexion ($P = 0.010$). For the non-dominant side in panel 1 F,

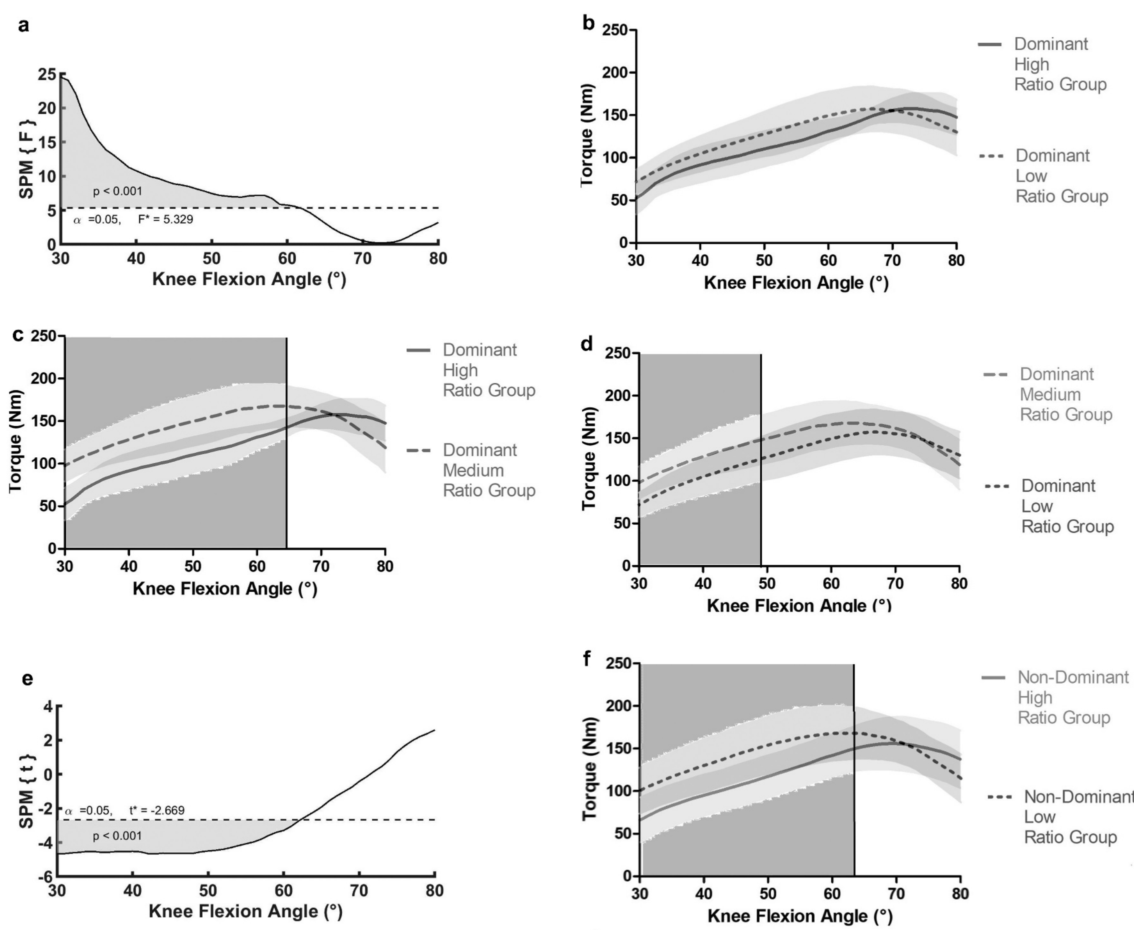

Figure 1. Illustrates the differences in absolute concentric knee extensor (conKE) torque at specific knee joint angles between different ratio groups. Figure 1A summarises significant differences between High, Medium and Low groups for the dominant lower limb. Figure 1B illustrates the differences between High and Low ratio groups for the dominant side. Figure 1C illustrates the differences between High and Medium ratio groups for the dominant side. Figure 1D illustrates the differences between Medium and Low ratio groups for the dominant side. Figure 1E summarises significant differences between High and Low groups for the non-dominant lower limb. Figure 1F illustrates the differences between High and Low ratio groups for the non-dominant side. The grey shaded areas of the figure represent significant differences between groups.

independent *t*-tests identified that the High DCR_{AST} group was significantly lower between 63° and 30° of knee flexion ($P < 0.001$; $d = 0.75$) than those grouped in the Low DCR_{AST} group.

When torque data were normalised to body mass for the dominant limb, one-way ANOVA identified a significant main effect for AST conKE across DCR_{AST} groups (Low, Medium and High) ($P < 0.001$; $\eta^2 = 0.094$). As illustrated by Figure 2, post hoc analysis in panel 2B revealed that the Low DCR_{AST} group was significantly higher compared to High DCR_{AST} group across 33–30° of knee flexion ($P = 0.049$). In panel 2C, the Medium DCR_{AST} group was also significantly higher than the High DCR_{AST} group between 62° and 30° of knee flexion ($P < 0.001$). In panel 2D, the Medium DCR_{AST} group were also significantly higher than the Low DCR_{AST} group between 43° and 30° of knee flexion ($P < 0.001$). For the non-dominant side in panel 2 F, the High DCR_{AST} was significantly higher between 80° and 75° of knee flexion ($P = 0.048$; $d = 0.076$) compared to those grouped in the Low DCR_{AST} group. Independent *t*-tests also identified that the High DCR_{AST} group was significantly lower between 63° and 30° of knee flexion ($P < 0.001$; $d = 0.78$) than those in the Low DCR_{AST} group.

As illustrated by Figure 3 for the dominant limb, one-way ANOVA identified a significant main effect for AST eccKF across DCR_{AST} groups (Low, Medium and High) ($P = 0.002$; $\eta^2 = 0.080$). Post hoc analysis in panel 3B revealed no significant differences between the torque-angle curve between High and Low DCR_{AST} groups across 80–30° of knee flexion ($P > 0.05$). However, in panel 3C, the Medium DCR_{AST} group was significantly lower than the High DCR_{AST} group between 80° and 30° of knee flexion ($P < 0.001$). In panel 3D, the Medium DCR_{AST} group were also significantly higher than the Low DCR_{AST} group between 36° and 30° of knee flexion ($P = 0.048$). For the non-dominant side in panel 3 F, independent t-test identified that the High DCR_{AST} group was significantly higher between 37° and 30° of knee flexion ($P = 0.046$; $d = 0.072$) compared to those grouped in the Low DCR_{AST} group.

When torque data were normalised to body mass for the dominant limb, one-way ANOVA identified a significant main effect for AST eccKF across DCR_{AST} groups (Low, Medium and High) ($P < 0.001$ $\eta^2 = 0.081$). As illustrated by Figure 4, post hoc analysis in panel 4B revealed no significant differences in the torque-angle curve between High and Low DCR_{AST} groups

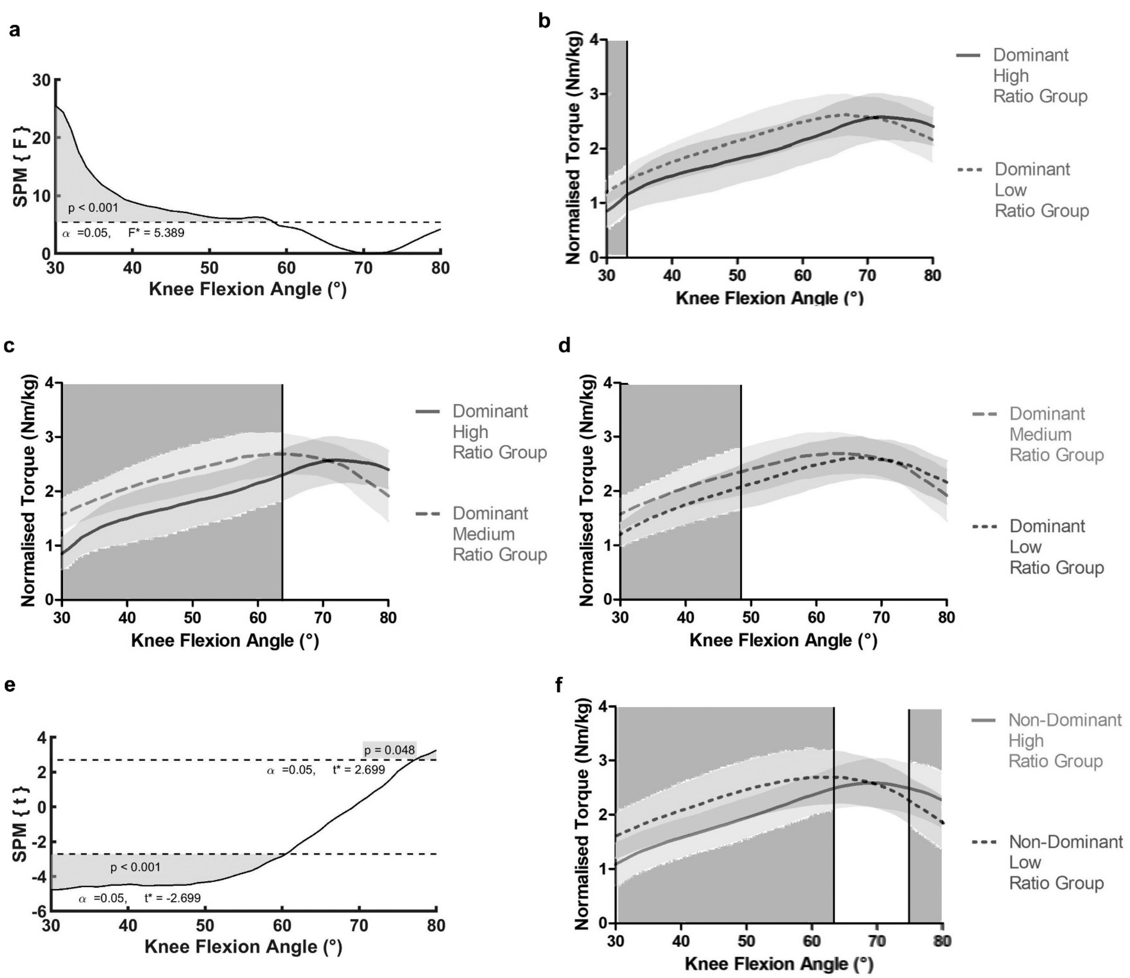

Figure 2. Illustrates the differences in absolute concentric knee extensor (conKE) torque at specific knee joint angles between different ratio groups. Figure 2A summarises significant differences between High, Medium and Low groups for the dominant lower limb. Figure 2B illustrates the differences between High and Low ratio groups for the dominant side. Figure 2C illustrates the differences between High and Medium ratio groups for the dominant side. Figure 2D illustrates the differences between Medium and Low ratio groups for the dominant side. Figure 2E summarises significant differences between High and Low groups for the non-dominant lower limb. Figure 2F illustrates the differences between High and Low ratio groups for the non-dominant side. The grey shaded areas of the figure represent significant differences between groups.

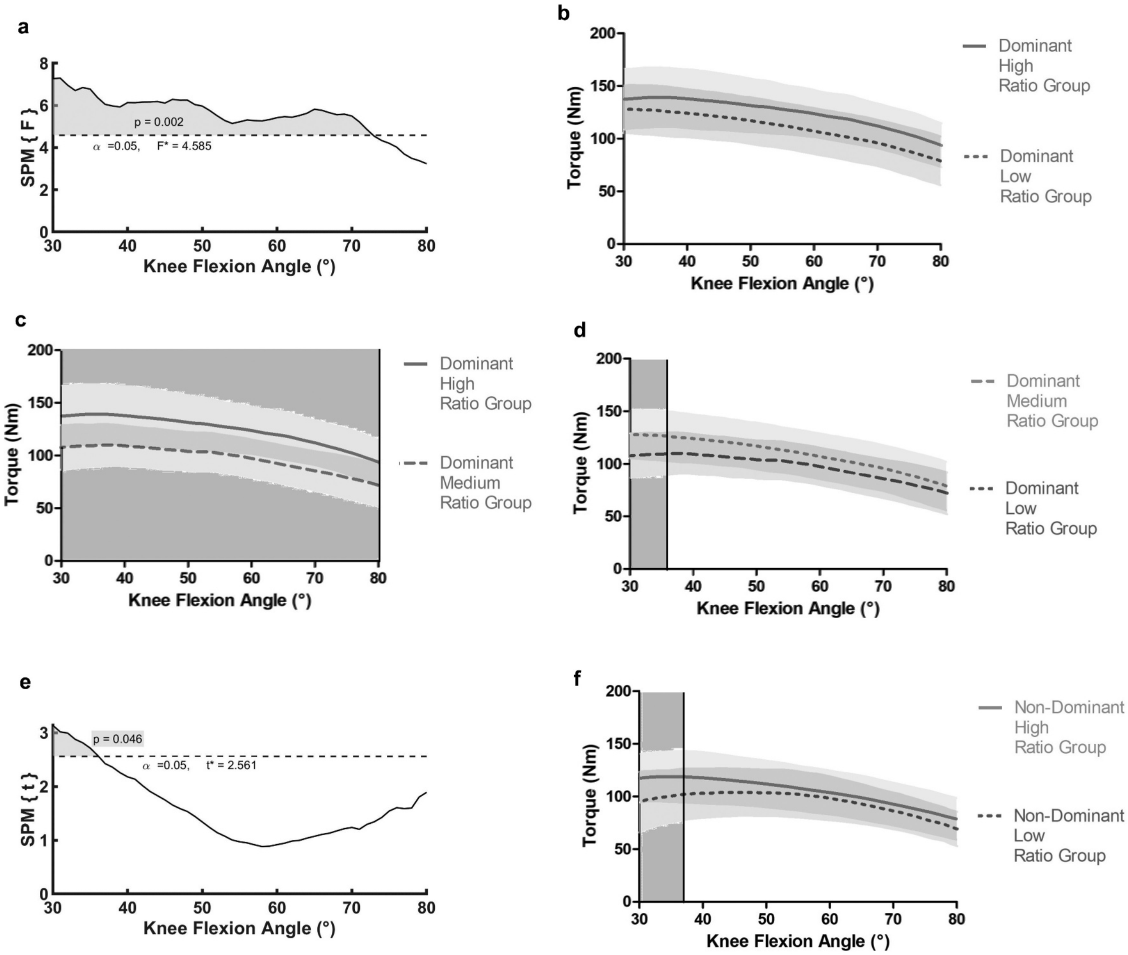

Figure 3. Illustrates the differences in absolute eccentric knee flexor (eccKF) torque at specific knee joint angles between different ratio groups. Figure 3A summarises significant differences between High, Medium and Low groups for the dominant lower limb. Figure 3B illustrates the differences between High and Low ratio groups for the dominant side. Figure 3C illustrates the differences between High and Medium ratio groups for the dominant side. Figure 3D illustrates the differences between Medium and Low ratio groups for the dominant side. Figure 3E summarises significant differences between High and Low groups for the non-dominant lower limb. Figure 3F illustrates the differences between High and Low ratio groups for the non-dominant side. The grey shaded areas of the figure represent significant differences between groups.

across 80–30° of knee flexion ($P > 0.05$). However, in panel 4C, the Medium DCR_{AST} group was significantly lower than the High DCR_{AST} group between 80° and 30° of knee flexion ($P < 0.001$). In panel 4D, the Medium DCR_{AST} group were also significantly higher than the Low DCR_{AST} group between 59° and 30° of knee flexion ($P < 0.001$). For the non-dominant side in panel 4 F, independent *t*-tests identified that the High DCR_{AST} group was significantly higher between 47° and 30°of knee flexion ($P = 0.021$; $d = 0.073$) compared to those grouped in the Low DCR_{AST} group.

Discussion

The purpose of this study was to assess whether isokinetic strength assessments of eccKF and conKE in professional female soccer players display differences when stratified into specific DCR_{AST} groups. The present study identified that those with higher DCR_{AST} values may not necessarily possess higher eccKF and lower conKE AST than those with lower DCR_{AST} values. The eccKF and conKE AST identified a consistent trend whereby the differences observed between DCR_{AST} groups were at increased knee extension angles, which advocates the need to identify strength data at specific joint angles, informing the choice of outcome metrics. When eccKF and conKE AST were scaled to body mass, differences were further pronounced for the torque-angle curve across a wider angular range, suggesting that relative strength measures also informs the choice outcome metrics. The interpretation of training needs are dependent on the outcome metrics practitioners use to profile strength, which subsequently informs exercise prescription for injury risk reduction, to monitor rehabilitation and return to play. Practitioners should interpret thigh musculature strength across the torque angle curve to quantify strength where the largest differences were observed to provide an enhanced clinical interpretation of data and informed exercise prescription.

The group differences in conKE and eccKF AST do not entirely support previous observations in professional male soccer, identifying that those who possess a higher DCR elicit increased eccKF and decreased conKE torques compared to Low DCR groups (Fritsch et al., 2020). Although similar results were observed for the non-dominant side in the present study to that of Fritsch et al. (2020), the Medium DCR_{AST} group's dominant limb elicited higher conKE AST than both High and Low DCR_{AST} groups. As such, these findings suggest a higher

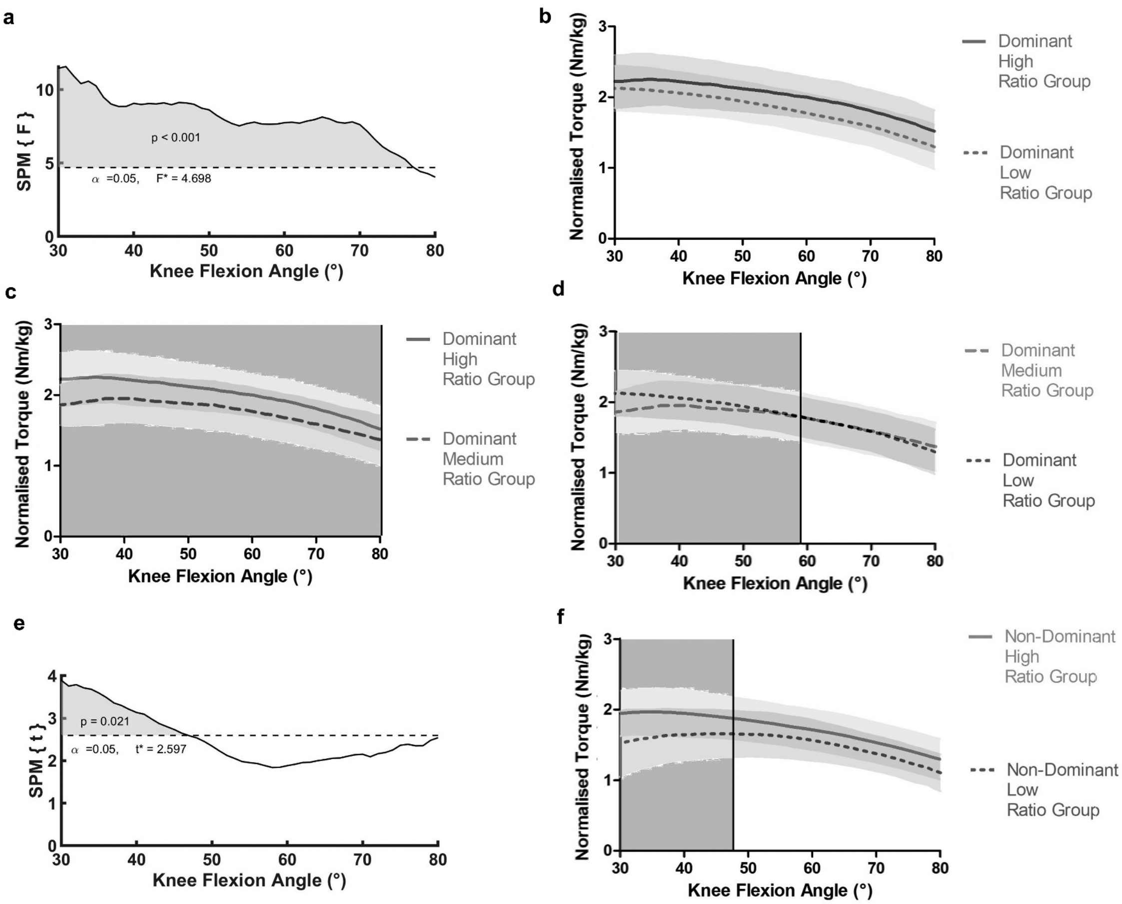

Figure 4. Illustrates the differences in absolute eccentric knee flexor (eccKF) torque at specific knee joint angles between different ratio groups. Figure 4A summarises significant differences between High, Medium and Low groups for the dominant lower limb. Figure 4B illustrates the differences between High and Low ratio groups for the dominant side. Figure 4C illustrates the differences between High and Medium ratio groups for the dominant side. Figure 4D illustrates the differences between Medium and Low ratio groups for the dominant side. Figure 4E summarises significant differences between High and Low groups for the non-dominant lower limb. Figure 4F illustrates the differences between High and Low ratio groups for the non-dominant side. The grey shaded areas of the figure represent significant differences between groups.

DCR_{AST} may not always be attributed to a combination of increased eccKF and decreased conKE AST. Typically a higher DCR would suggest these players may be at a decreased risk of knee flexor and knee ligament injuries due to reduced anterior shear forces exhibited at the joint (Doorenbosch & Harlaar, 2003; Kellis et al., 2003); however, it has yet to be determined if this observation is consistent with DCR_{AST}. For the non-dominant side, those with High DCR_{AST} group elicited lower conKE AST compared to the Low DCR_{AST} group, with potential implications for the completion of functional tasks specific to soccer and injury risk. The conKE are one of the primary dynamic knee stabilisers (Hughes & Watkins, 2006; Podraza & White, 2010), and are integral for the dissipation of large impact forces during the completion of functional tasks linked to risk of injury (Norcross et al., 2013; Podraza & White, 2010). The role of the conKE are also important during the completion of the propulsive phases of functional tasks such as jumping and sprinting, with implications for performance (Križaj et al., 2019). Consequently, if practitioners adopt DCR_{AST} as an outcome metric, this should be defined at precise knee joint angles due to the influence of different eccKF and conKE muscle lengths on torque production and contextualised in conjunction with the corresponding AST data.

When grouping DCR_{AST} using clustering algorithms, this present study consistently identified differences between the different sub-groups. Whilst these current observations generally suggest that higher DCR_{AST} groups elicited significantly higher and lower eccKF and conKE, respectively, this was not the case for the dominant limb between High and Low DCR_{AST} groups. The conKE AST were also not significantly different between High and Low DCR_{AST} groups, but did yield differences at 33–30° of knee flexion when scaled to body mass. This does not only reiterate the need to consider the corresponding torque value, but also consider strength proportionate to body mass (Zvijac et al., 2014). The present study also identified several differences at increased knee extension angles, and could be accounted for by increased fascicle lengths of the eccKF and conKE. As such, this enables the production of higher torques across a larger range of motion (Bourne et al., 2017; Seymore et al., 2017). Practitioners may therefore wish to consider profiling thigh musculature strength relative to body mass at increased knee extension angles, informing exercise prescription. The inclusion of AST data may subsequently help practitioners to prescribe exercise that promotes strength increases at targeted joint angles, which have been previously associated with consequent strength improvement (Barak et al., 2004). In turn, these approaches can be used to help reduce potential injury risk, identify rehabilitation responses and help inform return to play.

The present study did not control for injuries sustained over 3 months at the time of data collection, and must be considered a limitation. These present data can only be generalised to the current sample, care should be taken generalising beyond the specific population. Increased angular velocities were not used in this present study, with suggestions these assessments provide relevance to hopping tasks that are commonly performed in (p)rehabilitation (~300°·s^{-1}; Wang, 2011), but testing at extreme velocities substantially reduces the isokinetic range, thereby masking peak torques (Findley et al., 2006). The exclusion of higher velocities in this study were attributed to obtaining a sufficient range of motion during the isokinetic phase of the movement, as higher velocities shorten this range (Eustace et al., 2017), and that the sampling rate of the device cannot identify torque at each discrete joint angle. This presents the practitioner with a choice of a larger isokinetic range when using slower angular velocities, or greater angular velocities with a reduced isokinetic range. Moreover, isokinetic strength assessments are not accessible to all female soccer players due to expense, thus future research may wish to consider if AST are related to field-based strength assessments.

Conclusion

The present study observations advocate that practitioners should ensure that the corresponding torque data that calculates DCR is also considered for strength profiling of the thigh musculature, and across an angular range. The eccKF and conKE AST identified a consistent trend whereby the significant differences observed between groups were at increased knee extension angles, which advocates the need to identify strength data at specific joint angles, informing choice of outcome metrics. The inclusion of AST also enables practitioners to direct additional training needs. For example, the identified differences between the sub-groups, identified a consistent trend whereby differences in conKE and eccKF AST were noted at increased knee extension angles across both lower limbs, and when scaled to body mass. These approaches may help practitioners quantify thigh musculature strength at more functionally relevant knee joint angles that are more representative of functional tasks commonly performed by female soccer players associated with injury.

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References

Aagaard, P., Simonsen, E. B., Magnusson, S. P., Larsson, B., & Dyhre-Poulsen, P. (1998). A new concept for isokinetic hamstring: Quadriceps muscle strength ratio. *American Journal of Sports Medicine*, *26*(2), 231–237. https://doi.org/10.1177/03635465980260021201

Barak, Y., Ayalon, M., & Dvir, Z. (2004). Transferability of strength gains from limited to full range of motion. *Medicine and Science in Sports and Exercise*, *36*(8), 1413–1420. https://doi.org/10.1249/01.MSS.0000135777.01093.21

Bourne, M. N., Duhig, S. J., Timmins, R. G., Williams, M. D., Opar, D. A., Al Najjar, A., Kerr, G. K., & Shield, A. J. (2017). Impact of the nordic hamstring and hip extension exercises on hamstring architecture and morphology: Implications for injury prevention. *British Journal of Sports Medicine*, *51*(5), 469–477. https://doi.org/10.1136/bjsports-2016-096130

Campenella, B., Mattacola, C. G., & Kimura, I. F. (2000). Effect of visual feedback and verbal encouragement on concentric quadriceps and hamstrings peak torque of males and females. *Isokinetics and Exercise Science*, *8*(1), 1–6. https://doi.org/10.3233/IES-2000-0033

Cohen, J. (1988). Statistical power analysis for the behavior science. Hilsdale.

Cohen, D. D., Zhao, B., Okwera, B., Matthews, M. J., & Delextrat, A. (2015). Angle-specific eccentric hamstring fatigue after simulated soccer. *International Journal of Sports Physiology and Performance*, *10*(3), 325–331. https://doi.org/10.1123/ijspp.2014-0088

Croisier, J. L., Ganteaume, S., Binet, J., Genty, M., & Ferret, J. M. (2008). Strength imbalances and prevention of hamstring injury in professional soccer players: A prospective study. *American Journal of Sports Medicine*, *36*(8), 1469–1475. https://doi.org/10.1177/0363546508316764

De Ste Croix, M., ElNagar, Y. O., Iga, J., Ayala, F., & James, D. (2017). The impact of joint angle and movement velocity on sex differences in the functional hamstring/quadriceps ratio. *Knee*, *24*(4), 745–750. https://doi.org/10.1016/j.knee.2017.03.012

Della Villa, F., Buckthorpe, M., Grassi, A., Nabiuzzi, A., Tosarelli, F., Zaffagnini, S., & Della Villa, S. (2020). Systematic video analysis of ACL injuries in professional male football (soccer): Injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases. *British Journal of Sports Medicine*, *54*(23), 1423–1432. https://doi.org/10.1136/bjsports-2019-101247

Doorenbosch, C. A., & Harlaar, J. (2003). A clinically applicable EMG–force model to quantify active stabilization of the knee after a lesion of the anterior cruciate ligament. *Clinical Biomechanics*, *18*(2), 142–149. https://doi.org/10.1016/S0268-0033(02)00183-3

Eustace, S. J., Page, R. M., & Greig, M. (2017). Contemporary approaches to isokinetic strength assessments in professional soccer players. *Science and Medicine in Soccer*, *1*(3), 251–257. https://doi.org/10.1080/24733938.2017.1371851

Eustace, S. J., Page, R. M., & Greig, M. (2019). Isokinetic strength differences between elite senior and youth female soccer players identifies training requirements. *Physical Therapy in Sport*, *39*, 45–51. https://doi.org/10.1016/j.ptsp.2019.06.008

Eustace, S. J., Page, R. M., & Greig, M. (2020). Angle-Specific isokinetic metrics highlight strength training needs of elite youth soccer players. *Journal of Strength and Conditioning Research*, *34*(11), 3258–3265. https://doi.org/10.1519/JSC.0000000000002612

Findley, B. W., Brown, L. E., Whitehurst, M., Keating, T., Murray, D. P., & Gardner, L. M. (2006). The influence of body position on load range during isokinetic knee extension/flexion. *Journal of Sports Science & Medicine*, *5*(3), 400. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3842140/pdf/jssm-05-400.pdf

Fritsch, C. G., Dornelles, M. P., Oliveira, G. D. S., & Baroni, B. M. (2020). Poor hamstrings-to-quadriceps torque ratios in male soccer players: Weak hamstrings, strong quadriceps, or both? *Sports Biomechanics*, 1–11. https://doi.org/10.1080/14763141.2020.1766100

Genolini, C., Ecochard, R., Benghezal, M., Driss, T., Andrieu, S., Subtil, F., & Huang, C.-H. (2016). kmlShape: An efficient method to cluster longitudinal data (Time-Series) according to their shapes. *PLoS ONE*, *11*(6), 1–24. https://doi.org/10.1371/journal.pone.0150738

Gordon, D., Hughes, F., Young, K., Scruton, A., Keiller, D., Caddy, O., Baker, J., & Barnes, R. (2013). The effects of menstrual cycle phase on the development of peak torque under isokinetic conditions. *Isokinetics and Exercise Science*, *21*(4), 285–291. https://doi.org/10.3233/IES-130499

Greig, M. (2008). The influence of soccer-specific fatigue on peak isokinetic torque production of the knee flexors and extensors. *The American Journal of Sports Medicine*, *36*(7), 1403–1409. https://doi.org/10.1177/0363546508314413

Gür, H., Akova, B., Pündük, Z., & Küçükoğlu, S. (1999). Effects of age on the reciprocal peak torque ratios during knee muscle contractions in elite soccer players. *Scandinavian Journal of Medicine & Science in Sports*, *9*(2), 81–87. https://doi.org/10.1111/j.1600-0838.1999.tb00213.x

Hägglund, M., & Waldén, M. (2016). Risk factors for acute knee injury in female youth soccer. *Knee Surgery, Sports Traumatology, Arthroscopy*, *24*(3), 737–746. https://doi.org/10.1007/s00167-015-3922-z

Hewett, T. E., & Myer, G. D. (2011). The mechanistic connection between the trunk, hip, knee, and anterior cruciate ligament injury. *Exercise and Sport Sciences Reviews*, *39*(4), 161–166. https://doi.org/10.1097/JES.0b013e3182297439

Hughes, G., & Watkins, J. (2006). A risk-factor model for anterior cruciate ligament injury. *Sports Medicine*, *36*(5), 411–428. https://doi.org/10.2165/00007256-200636050-00004

Kellis, E., Arabatzi, F., & Papadopoulos, C. (2003). Muscle co-activation around the knee in drop jumping using the co-contraction index. *Journal of Electromyography and Kinesiology*, *13*(3), 229–238. https://doi.org/10.1016/S1050-6411(03)00020-8

Križaj, J., Rauter, S., Vodičar, J., Hadžić, V., & Šimenko, J. (2019). Predictors of vertical jumping capacity in soccer players. *Isokinetics and Exercise Science*, *27*(1), 9–14. https://doi.org/10.3233/IES-182138

Le Gall, F., Carling, C., & Reilly, T. (2008). Injuries in young elite female soccer players: An 8-season prospective study. *American Journal of Sports Medicine*, *36*(2), 276–284. https://doi.org/10.1177/0363546507307866

Lee, J. W. Y., Mok, K. M., Chan, H. C. K., Yung, P. S. H., & Chan, K. M. (2018). Eccentric hamstring strength deficit and poor hamstring-to-quadriceps ratio are risk factors for hamstring strain injury in soccer: A prospective study of 146 professional players. *Journal of Science and Medicine in Sport*, *21*(8), 789–793. https://doi.org/10.1016/j.jsams.2017.11.017

Lucarno, S., Zago, M., Buckthorpe, M., Grassi, A., Tosarelli, F., Smith, R., & Della Villa, F. (2021). Systematic video analysis of anterior cruciate ligament injuries in professional female soccer players. *The American Journal of Sports Medicine*, 03635465211008169. https://doi.org/10.1177/03635465211008169

Marchant, D. C., & Greig, M. (2017). Attentional focusing instructions influence quadriceps activity characteristics but not force production during isokinetic knee extensions. *Human Movement Science*, *52*, 67–73. https://doi.org/10.1016/j.humov.2017.01.007

Marchant, D. C., Greig, M., & Scott, C. (2009). Attentional focusing instructions influence force production and muscular activity during isokinetic elbow flexions. *Journal of Strength and Conditioning Research*, *23*(8), 2358–2366. https://doi.org/10.1519/JSC.0b013e3181b8d1e5

Montalvo, A. M., Schneider, D. K., Silva, P. L., Yut, L., Webster, K. E., Riley, M. A., Kiefer, A. W., Doherty-Restrepo, J. L., & Myer, G. D. (2019). "What's my risk of sustaining an ACL injury while playing soccer (soccer)?" A systematic review with meta-analysis. *British Journal of Sports Medicine*, *53*(21), 1333–1340. http://dx.doi.org/10.1136/bjsports-2016-096274

Norcross, M. F., Lewek, M. D., Padua, D. A., Shultz, S. J., Weinhold, P. S., & Blackburn, J. T. (2013). Lower extremity energy absorption and biomechanics during landing, part II: Frontal-plane energy analyses and interplanar relationships. *Journal of Athletic Training*, *48*(6), 757–763. https://doi.org/10.4085/1062-6050-48.4.10

Podraza, J. T., & White, S. C. (2010). Effect of knee flexion angle on ground reaction forces, knee moments and muscle co-contraction during an impact-like deceleration landing: Implications for the non-contact mechanism of ACL injury. *Knee*, *17*(4), 291–295. https://doi.org/10.1016/j.knee.2010.02.013

Rae, D. E., Stephenson, K. J., & Roden, L. C. (2015). Factors to consider when assessing diurnal variation in sports performance: The influence of chronotype and habitual training time-of-day. *European Journal of Applied Physiology*, *115*(6), 1339–1349. https://doi.org/10.1007/s00421-015-3109-9

Seymore, K. D., Domire, Z. J., DeVita, P., Rider, P. M., & Kulas, A. S. (2017). The effect of Nordic hamstring strength training on muscle architecture, stiffness, and strength. *European Journal of Applied Physiology*, *117*(5), 943–953. https://doi.org/10.1007/s00421-017-3583-3

Siddle, J., Greig, M., Weaver, K., Page, R. M., Harper, D., & Brogden, C. M. (2019). Acute adaptations and subsequent preservation of strength and speed measures folLowing a Nordic hamstring curl intervention: A randomised controlled trial. *Journal of Sports Sciences*, *37*(8), 911–920. https://doi.org/10.1080/02640414.2018.1535786

Suarez-Arrones, L., Lara-Lopez, P., Rodriguez-Sanchez, P., Lazaro-Ramirez, J. L., Salvo, V. D., Guitart, M., Fuentes-Nieto, C., Rodas, G., Mendez-Villanueva, A., & Lucía, A. (2019). Dissociation between changes in sprinting performance and Nordic hamstring strength in professional male soccer players. *PLoS ONE*, *14*(3), 1–12. https://doi.org/10.1371/journal.pone.0213375

Van Dyk, N., Bahr, R., Burnett, A. F., Whiteley, R., Bakken, A., Mosler, A., Farooq, A., & Witvrouw, E. (2017). A comprehensive strength testing protocol offers no clinical value in predicting risk of hamstring injury: A prospective cohort study of 413 professional football players. *British Journal of Sports Medicine*, *51*(23), 1695–1702. https://doi.org/10.1136/bjsports-2017-097754

Van Dyk, N., Bahr, R., Whiteley, R., Tol, J. L., Kumar, B. D., Hamilton, B., Farooq, A., & Witvrouw, E. (2016). Hamstring and quadriceps isokinetic strength deficits are weak risk factors for hamstring strain injuries. *American Journal of Sports Medicine*, *44*(7), 1789–1795. https://doi.org/10.1177/0363546516632526

Wang, L. I. (2011). The lower extremity biomechanics of single-and double-leg stop-jump tasks. *Journal of Sports Science & Medicine*, *10*(1), 151–156. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3737885/pdf/jssm-10-151.pdf

Zvijac, J. E., Toriscelli, T. A., Merrick, W. S., Papp, D. F., & Kiebzak, G. M. (2014). Isokinetic concentric quadriceps and hamstring normative data for elite collegiate American soccer players participating in the NFL scouting combine. *Journal of Strength and Conditioning Research*, *28*(4), 875–883. https://doi.org/10.1519/JSC.0b013e3182a20f19