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The influence of soccer-specific exercise on isokinetic angle-specific thigh musculature strength in female soccer players

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ABSTRACT

This study assessed the influence of soccer-specific exercise on thigh musculature strength in female soccer players. Eight amateur female soccer players (age 24 ± 6 years; height 163 ± 8 cm; mass 68 ± 11 kg) participated in the study. Participants completed the female match simulation-90 (FEMS-90), replicating a 90-minute match. Isokinetic strength assessments of the concentric knee extensors (conKE), concentric knee flexors (conKF), eccentric knee extensors (eccKE) and eccentric knee flexors (eccKF) for the dominant lower limb were conducted at $60°\cdot s^{-1}$ where conventional ratios (CR) and dynamic control ratios (DCR) were determined. All strength data were expressed as angle-specific torque (AST). A Bayesian approach identified a 66–78% probability that AST of all muscle actions were lower post SSEP, and a 57–66% probability of a difference that CR_{AST} and DCR_{AST} were lower post SSEP across all angles. The results of this study provides unique insight into how female soccer players respond to soccer match-play, and may have implications for potential injury risk, exercise prescription and recovery. Moreover, given the prevalence and burden of knee ligament injuries in female soccer players, this study provides insight into thigh musculature strength acutely responds following simulated match-play.

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Female soccer-specific fatigue; dynamic control ratio; angle-specific; knee extensors; knee flexors; isokinetic dynamometry

Introduction

Epidemiological research in female soccer players has identified that injury incidence from match-play is approximately 20 injuries per 1000 hours, with 85% of these injuries concerning the lower limb (Horan et al., 2023; Mayhew et al., 2021), specifically knee ligaments (23%) and thigh muscular strain injuries (21%) (Faude et al., 2006; Horan et al., 2023; Le Gall et al., 2008). Such injuries are most likely to occur during sprinting, high-speed running and change of direction tasks during soccer match-play (Horan et al., 2023; Mayhew et al., 2021). Although injuries are typically multifactorial in nature, thigh muscular strength deficits have been suggested to play a role in increasing a players injury susceptibility (Croisier et al., 2008; Lee et al., 2018). Where equivocal evidence exists (Van Dyk et al., 2016, 2017), this could be a result of methods use to record strength responses, or limitations of the metrics used to quantify strength. Isokinetic dynamometry (IKD) offers the gold standard method to measure strength characteristics (Stark et al., 2011), but there is often a reliance on a select number of metrics which typically only provide one-point measurements along the torque-angle curve, such as peak torque. As such, angle-specific torques have been more recently advocated in female soccer players (Eustace et al., 2019, 2022), and can quantify strength parameters at knee joint angles where injury is more likely to occur (Croisier et al., 2008; della Villa et al., 2020; Lee et al., 2018; Lucarno et al., 2021).

Beyond the issues with the way in which isokinetic data is typically analysed, there is also an argument that the way in which these assessments are conducted should also be advanced. For example, limited research considers eccentric knee extensor actions, with fewer still recording such data in female populations. This is somewhat remiss when considering that during injury inciting movements (cutting, landing, decelerating), one of the primary controlling actions of the lower limbs is that of eccentric actions of the knee extensors (Norcross et al., 2013; Podraza & White, 2010). Similarly, there is also a need to consider that isokinetic assessments should also be conducted in fatigued states to increase the specificity of the assessments to the timing of injuries during match play (Doyle et al., 2021). For example, research suggests that anterior cruciate ligament (ACL) injuries are heightened towards the end of each half (Doyle et al., 2021), with the greatest change in mechanical fatigue occurring towards the end of the first half with a further gradual reduction thereafter. As such, there is a need to conduct isokinetic strength assessments that afford more insight into these types of muscle actions. These isokinetic strength assessments should be conducted at $60°\cdot s^{-1}$ rather than higher testing velocities to better identify angle-specific data across the torque-angle curve (Eustace et al., 2022) for quantifying the effect of female soccer-specific activity.

It has also been suggested that fatigue is a risk factor for thigh musculature and knee ligament injuries in female soccer players given that these injuries may be more likely to occur

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during the second half of competitive match-play (Doyle et al., 2021). In support of these observations, further evidence in male soccer players is largely in agreement that soccer-specific exercise, such as free-running and treadmill-based simulations of soccer match-play have seen reductions in thigh musculature strength and strength ratios, particularly the eccentric knee flexors (Field et al., 2022; Greig, 2008; Page & Greig, 2020; Small et al., 2010). However, the evidence base regarding female soccer players and angle-specific strength responses following soccer-specific exercise is currently sparse. Current evidence into the soccer-specific effects of thigh musculature strength in females have identified reductions in peak torques, especially those of the eccentric knee flexors at increased knee extension angles, and lower strength ratios, potentially increasing risk of injury to knee ligaments and of the thigh musculature (De Ste Croix et al., 2015; Ferguson et al., 2023). However, the findings from these studies must be interpreted with caution as the soccer-specific simulations used to induce fatigue were not based on female soccer match-play (De Ste Croix et al., 2015; Ferguson et al., 2023). As the SAFT90 and BEAST90 were used to induce soccer-specific fatigue, and given these simulations are based on male match-play data, these observations may not accurately reflect the demands of female soccer match-play as these requirements are sex specific (Datson et al., 2014). With a growing appreciation of the demands of female soccer, adapting currently available male soccer-simulations by arbitrary reducing total distance or speed should not be utilised in an attempt to better represent the demands of female match-play demands. There is therefore a need to develop and utilise female-specific protocols, based on population-specific notational data, and eliciting a response more specific to female match-play. Such female soccer-specific simulations should be free running rather than conducted on a treadmill to better replicate utility movements and changes of direction which would further elicit changes in strength responses in thigh musculature. Moreover, given the prevalence and burden of knee ligament injuries in female soccer players, this study may provide insight into how thigh musculature strength could acutely respond following simulated match-play. In turn, this may have implications for potential injury risk, exercise prescription and recovery.

Therefore, the primary aim of this study was to quantify the effect of a novel female soccer simulation of thigh musculature strength indices in amateur female soccer players. A secondary aim of the study was to present a novel female soccer-simulation that is based on the demands of female soccer-match play data. It was hypothesised that there would be reductions in angle-specific torques and ratios following a female soccer simulation.

Materials and methods

Following ethics approval alongside written informed consent, eight amateur female soccer players (age 24 ± 6 years; height 163 ± 8 cm; mass 68 ± 11 kg) within the English Birmingham women's county league, and from the same team, participated within the study. All players were free from lower limb injury for three months at the time of testing. 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, except familiarisation to the soccer-simulation was only 15 minutes to ensure participants understood the instruction of the audio commands. 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 (cm) was measured using a stadiometer (Model 220, Seca, Hamburg, Germany), and body mass (kg) was measured by digital floor standing scales (Model 770, Seca, Hamburg, Germany. 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 60W, followed by dynamic stretches (10 reps of lunges, body-weight squats and countermovement jumps).

Isokinetic strength assessments of the concentric knee extensors (conKE), concentric knee flexors (conKF), eccentric knee extensors (eccKE) and eccentric knee flexors (eccKF) for the dominant lower limb were conducted on a Cybex isokinetic dynamometer (Cybex Humac-Norm, Lumex, Ronkonkoma, NY, USA) at $60°\cdot s^{-1}$. Research has identified acceptable reliability via interclass correlation coefficients (ICCs) that are > 0.8 in female soccer players (Eustace et al., 2019). A familiarisation of sub-maximal (75% effort) trial run through at each muscle group and muscle action was performed prior to initiating full maximal effort readings during the experimental trial. Thereafter, participants began the protocol of instructed maximal effort for 5 repetitions for each for all muscle group and muscle action, with 60-second rest between sets (Greig, 2008). Throughout the strength assessments, verbal encouragement of 'Push' and 'Pull' were standardised.

The range of motion (ROM) of the knee joint was set at 20–85° during isokinetic strength assessments (0° = full extension), and gravity corrected at 20° of knee flexion in accordance with the manufacturer's guidelines. This ROM selected to ensure quality of the data, comfort, and risk of injury to each participant. 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.

Participants then completed the female match simulation-90 (FEMS-90) (Figure 1), replicating 90-minute soccer match-play demands. The FEMS-90 was developed based on the notational data presented by Datson et al. (2014). This study provides detailed data on Average Effort Distance (m), Total Distance (m), Average Effort Duration (s), Total Time (s), Average Effort Velocity ($m\cdot s^{-1}$), and Average Effort Velocity ($km\cdot h^{-1}$) for commonly performed actions during female match play, including Stand, Walk, Jog, Run (LSR), Stride (HSR), Sprint, and Backwards movements. Specifically, the

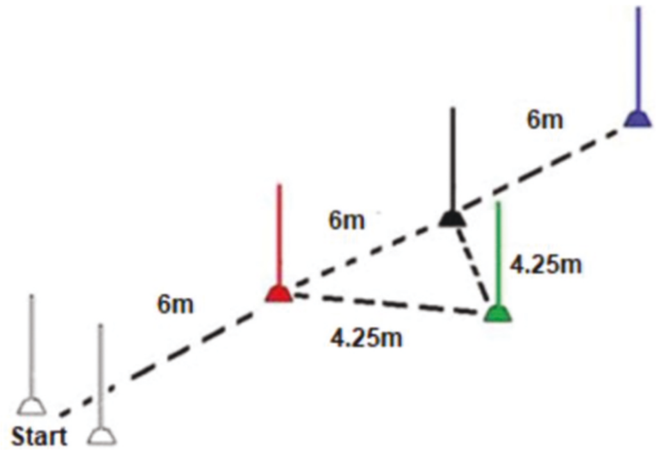

Figure 1. Schematic of the SSEP agility course.

notational data for these actions were adapted from Datson et al. (2014) and used to structure the simulation protocol. The FEMS-90 was designed to replicate the type, duration, and intensity of these actions, ensuring ecological validity with typical female match-play patterns. This process involved matching the proportion of time and distance for each action to the values reported by Datson et al. (2014), thereby creating a simulation that closely mirrors the physical and physiological demands of competitive female soccer. The protocol covers 18-metres (6-metre increments marked as start, red, green, black and blue aiding instruction direction) including a lateral cutting manoeuvre (4.25 metres) (between 6 and 12 metres) (Datson et al., 2014). Auditory instructions informed participants with commands 'walk', 'stand', 'jog', 'jog backwards', 'stride', 'run' and 'sprint' covering different locomotion intensities with instruction transferred from text to speech v10.12.6 (Apple Inc. CA, USA) to Garageband v10.3.3 for Mac (Apple Inc. CA, USA) and an audio file was uploaded to iTunes v12.8.0.150 (Apple Inc, CA, USA) for playback. Due to the original SSEP duration lasting 2 bouts of 15 minutes for the replication of 90 minutes, audio was repeated for 6 × 15-minute bouts. Table 1 displays descriptive characteristics of the SSEP and notational data on which it is based upon (Datson et al., 2014), allowing for better replication female soccer match-play.

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 (Baumgart et al., 2018) using a customised script in R (R Core Team, 2023). The isokinetic phase was then identified at the constant angular velocity by applying a 1% cut-off in Microsoft Excel (Eustace et al., 2022). A conservative approach was used to ensure that the data were truly isokinetic by applying a 1% cut-off of the angular velocity, and as such, the isokinetic phase was determined between 59.4 and $60.6°\cdot s^{-1}$. This was performed by extracting an MS Excel file of the raw data file that included torque, time, position and angular velocity for all muscle actions performed and used for further analysis. Due to acceleration of the input arm of the IKD towards the end of an individual's ROM, an isokinetic range of 30–75° was used for further analysis as this angular range was achieved for all participants for each muscle action. The mean and standard deviation for the isokinetic phase of different muscle actions and muscle groups are provided by Table 2. Thereafter, the conventional strength ratio (CR_{AST}) was defined as conKF/conKE, the dynamic control ratio 1 ($DCR1_{AST}$) was defined as eccKF/conKE and the dynamic control ratio 2 ($DCR2_{AST}$) was defined as conKF/eccKE. The AST and strength ratios of the knee flexors and extensors were identified at each angle across a consistent angular range between 75° and 30°. Data were expressed as absolute values for AST and DCR_{AST} and not normalised to body mass given that this study design was a within-subject comparison.

The influence of soccer-specific exercise on angle-specific torques and strength ratios were determined by using

Table 1. The activity profile associated with the female soccer-specific exercise protocol including notational data (adapted from normative data: Datson et al., 2014.).

		Frequency	Average Effort Distance (m)	Total Distance (m)	Average Effort Duration (s)	Total Time (s)	Average Effort Velocity ($m\cdot s^{-1}$)	Average Effort Velocity ($km.h^{-1}$)
Stand	Notational	25	0	0	8	200	0	0
	FEMS-90	24	0	0	8	192	0	0
Walk	Notational	92	6	554	4	368	1.5	5.4
	FEMS-90	57	10	570	6.5	370.5	1.5	5.4
Jog	Notational	36	18	648	5	180	3.5	12.6
	FEMS-90	36	18	646	5	180	3.5	12.6
Run (LSR)	Notational	15	18	270	4	60	4.5	16.2
	FEMS-90	13	16	208	4	52	4	14.4
Stride (HSR)	Notational	6	6	36	1.25	7.3	4.8	17.3
	FEMS-90	6	6	36	1.25	7.3	4.8	17.3
Sprint	Notational	6	6	36	1	6	6	21.6
	FEMS-90	6	12	72	2	12	6	21.6
Backwards	Notational	10	18	180	6	60	3	10.8
	FEMS-90	9	18	162	7	63	2.6	9.4

Table 2. Descriptive statistics for isokinetic phase for muscle group and action (mean ± standard deviation).

	End of Flexion	End of Extension
Concentric Knee Extensors (°)	24.63 ± 2.83	77.88 ± 2.31
Concentric Knee Flexors (°)	25.50 ± 2.56	77.43 ± 2.23
Eccentric Knee Extensors (°)	24.63 ± 2.83	77.32 ± 1.40
Eccentric Knee Flexors (°)	26.13 ± 2.53	76.57 ± 1.46

a Bayesian approach using Thin-Plate Splines. A Bayesian approach was used given the common misinterpretation of traditional *p* values, and that a Bayesian approach is more appropriate for smaller sample sizes. Bayesian analysis allows the integration of prior knowledge or expert opinion into the analysis through the use of prior distributions. This is especially beneficial with small samples, as the prior can supplement the limited data, leading to more stable and credible parameter estimates. Equally, Bayesian analysis provides direct probability statements about parameters, facilitating intuitive interpretations. For instance, one can compute the probability that a parameter lies within a specific interval, which is particularly useful when data are scarce and uncertainty is high. Finally, in small sample contexts, models are prone to overfitting. Bayesian regularisation can mitigate this risk by effectively shrinking parameter estimates towards the prior mean (He et al., 2021; Mengersen et al., 2016). The prior for the intercept (α) was a student-t distribution with 3 degrees of freedom, the location parameter (μ) was set to the median of the response variable, and the scale parameter (σ) was set to the median absolute deviation of the response variable. The prior distribution for the regression coefficients (β) was a wide normal distribution. Subsequent comparisons to determine the best model were performed using Leave-One-Out-Cross-Validation, with skew-normal distributions demonstrating better fit. In addition to calculating the probability of a group difference being greater than zero, the probability of a difference above the Smallest Worthwhile Change (within group standard deviation multiplied by a small effect size of 0.2) plus the coefficient of variation (standard deviation/mean multiplied by 100) were used to determine if these differences may be meaningful. The use of 0.2 in defining the smallest worthwhile change aligns with established statistical conventions for small effect sizes. This practice facilitates the interpretation of Bayesian analysis outcomes by providing a benchmark for assessing the practical significance of observed changes. This approach is grounded in the conventions established by Jacob Cohen (Cohen, 1988), who characterised an effect size of 0.2 as 'small' but meaningful. Even though Hopkin's methodology (Hopkins et al., 2009) has been criticised in terms of treating frequentist confidence intervals as if they were Bayesian credible intervals, this suggestion that a standardised difference greater than 0.2 is reasonable smallest worthwhile change is not at issue. All analyses were conducted using R (R Core Team, 2023) using Bayesian Regression Models in Stan (brms) package (Bürkner, 2017) to implement a Hamiltonian Markov Chain Monte Carlo with a No-U-Turn Sampler. All models were checked for convergence (R-hat = 1), with graphical posterior predictive checks showing how the predicted distribution compared to the observed data (Gabry et al., 2019). To illustrate the uncertainty around the estimation of group differences, lower and upper 95% Higher Density Intervals (HDI) are reported along with means ± standard deviation.

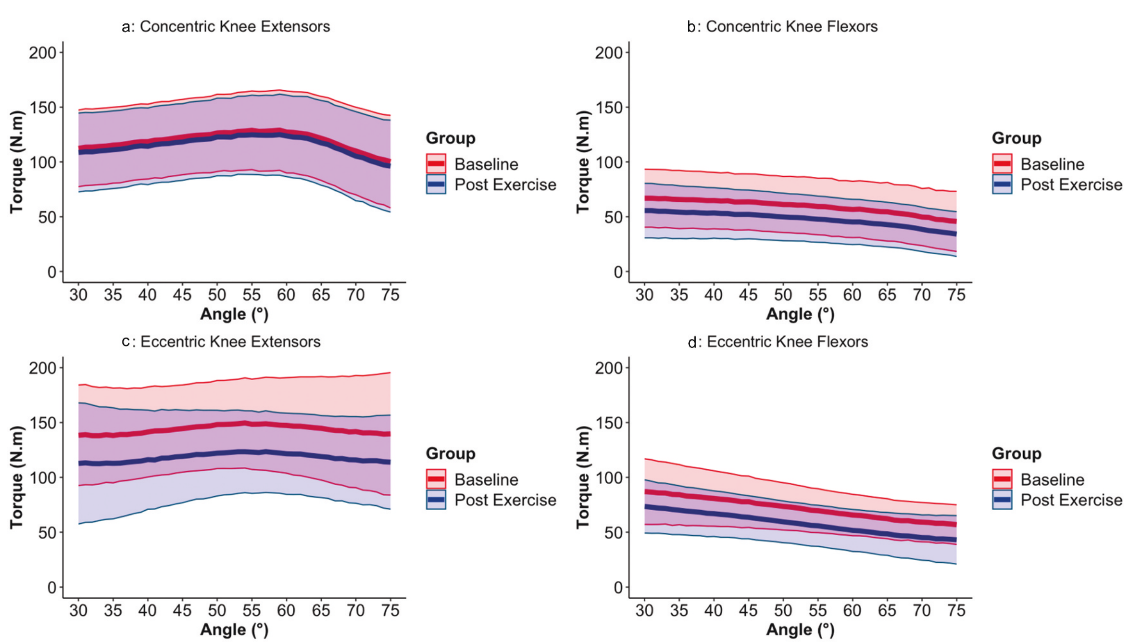

Figure 2. Illustrates the influence of soccer-specific exercise on angle-specific torque. Figure 2A illustrates concentric knee extensors (conKE) at baseline and post exercise. Figure 2B illustrates concentric knee flexors (conKF) at baseline and post exercise. Figure 2C illustrates eccentric knee extensors (eccKE) at baseline and post exercise. Figure 2D illustrates eccentric knee extensors (eccKF) at baseline and post exercise.

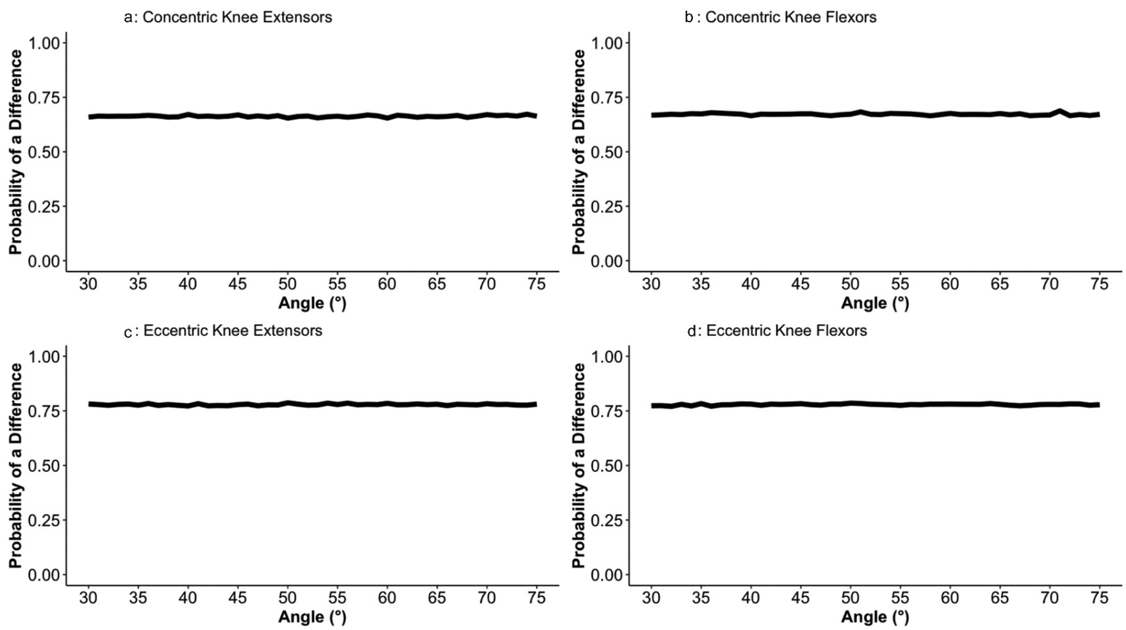

Figure 3. Illustrates the influence of soccer-specific exercise on the probability of a difference for angle-specific torque. Figure 3A illustrates concentric knee extensors (conKE) at baseline and post exercise. Figure 3B illustrates concentric knee flexors (conKF) at baseline and post exercise. Figure 3C illustrates eccentric knee extensors (eccKE) at baseline and post exercise. Figure 3D illustrates eccentric knee extensors (eccKF) at baseline and post exercise.

Results

The influence of soccer-specific fatigue on AST is summarised by Figure 2, with data expressed as mean ± standard deviation. As illustrated by Figure 3(a), there was a ~ 66% probability of conKE being higher at baseline when compared to post exercise across all knee joint angles. Figure 3(b) illustrates a ~ 67% probability of conKF being higher at baseline when compared to post exercise across all knee joint angles. Figure 3(c) illustrates a ~ 78% probability of eccKE being higher at baseline when compared to post exercise across all knee joint angles. Figure 3(d) illustrates a ~ 77% probability of eccKF being higher at baseline when compared to post exercise across all knee joint angles. Figure 4 illustrates the mean difference with lower and upper 95% HDIs for AST at baseline when compared to post exercise across all knee joint angles Additionally, the probability of a difference higher than the CV+SWC was 0% across all knee joint angles for all muscle actions.

The influence of soccer-specific fatigue on strength ratios is summarised by Figure 5, with data expressed as mean ± standard deviation. As illustrated by Figure 6(a), there was

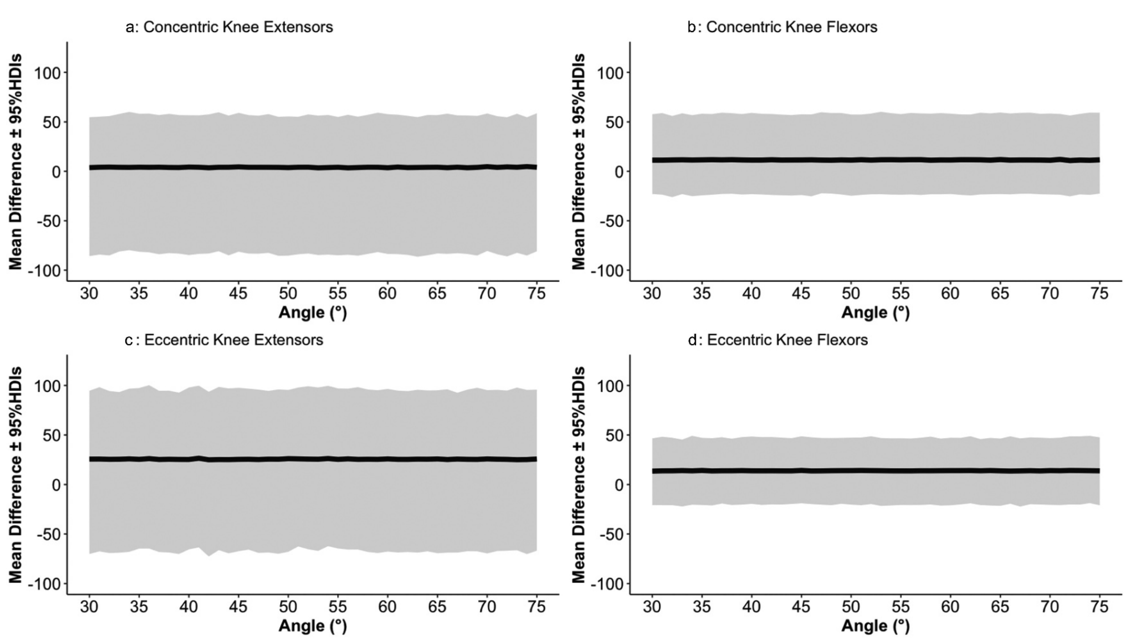

Figure 4. Illustrates the influence of soccer-specific exercise on the HDI of a difference for angle-specific torque figure 4A illustrates concentric knee extensors (conKE) at baseline and post exercise. Figure 4B illustrates concentric knee flexors (conKF) at baseline and post exercise. Figure 4C illustrates eccentric knee extensors (eccKE) at baseline and post exercise. Figure 4D illustrates eccentric knee extensors (eccKF) at baseline and post exercise.

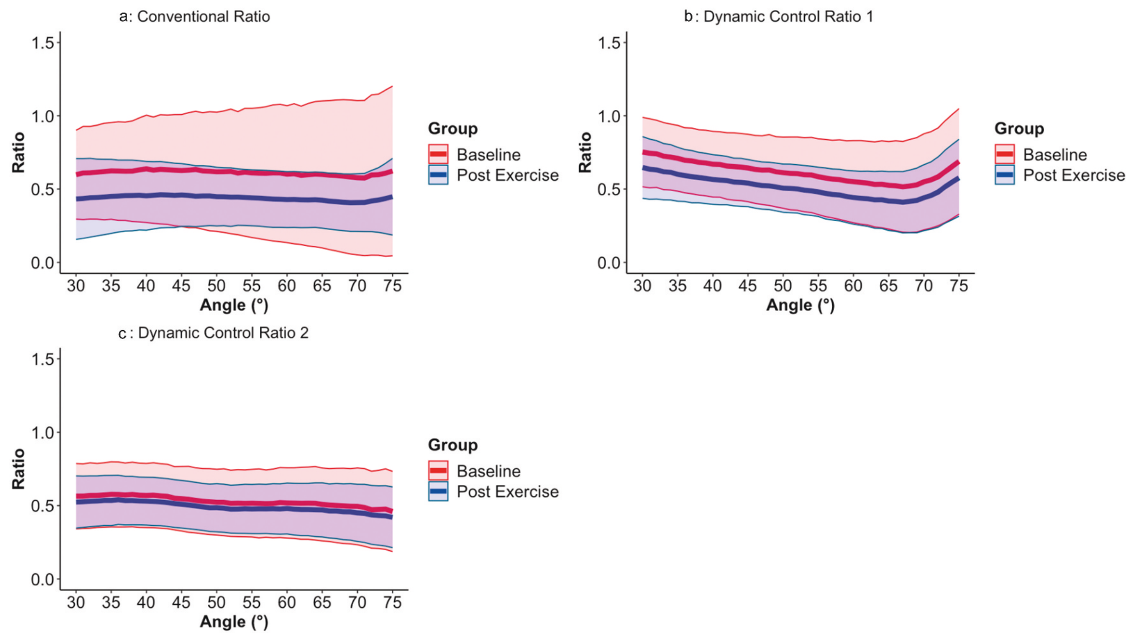

Figure 5. Illustrates the influence of soccer-specific exercise on angle-specific strength ratios. Figure 5A illustrates the conventional strength ratio (conKF/conKE) at baseline and post exercise. Figure 5B illustrates the dynamic control ratio 1 (eccKF/conKE) at baseline and post exercise. Figure 5C illustrates the dynamic control ratio 1 (conKF/eccKE) at baseline and post exercise.

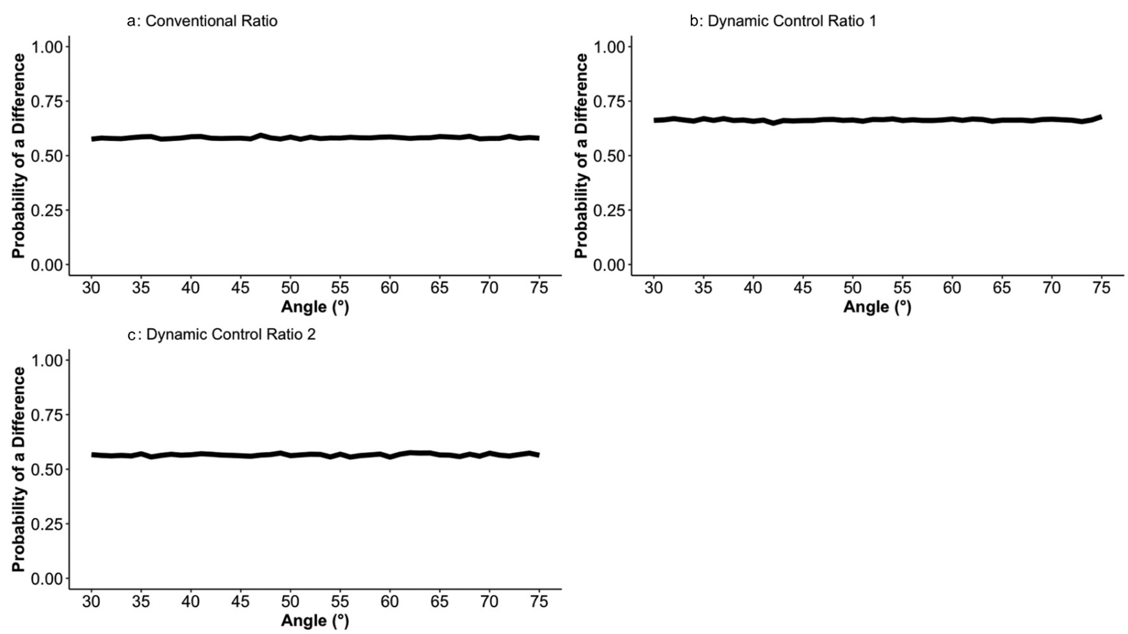

Figure 6. Illustrates the influence of soccer-specific exercise on the probability of a difference for angle-specific strength ratios. Figure 6A illustrates the conventional strength ratio (conKF/conKE) at baseline and post exercise. Figure 6B illustrates the dynamic control ratio 1 (eccKF/conKE) at baseline and post exercise. Figure 6C illustrates the dynamic control ratio 1 (conKF/eccKE) at baseline and post exercise.

a ~ 58% probability of CR_{AST} being higher at baseline when compared to post exercise across all knee joint angles. Figure 6(b) illustrates a ~ 66% probability of $DCR1_{AST}$ being higher at baseline when compared to post exercise across all knee joint angles. Figure 6(c) illustrates a ~ 57% probability of $DCR2_{AST}$ being higher at baseline when compared to post exercise across all knee joint angles. Figure 7 illustrates the mean difference with lower and upper 95% HDIs for AST at baseline when compared to post exercise across all knee joint angles Additionally, the probability of a difference higher than the CV+SWC was 0% across all knee joint angles for all muscle actions.

Discussion

The primary aim of this study was to quantify the effect of a novel female soccer simulation of thigh musculature

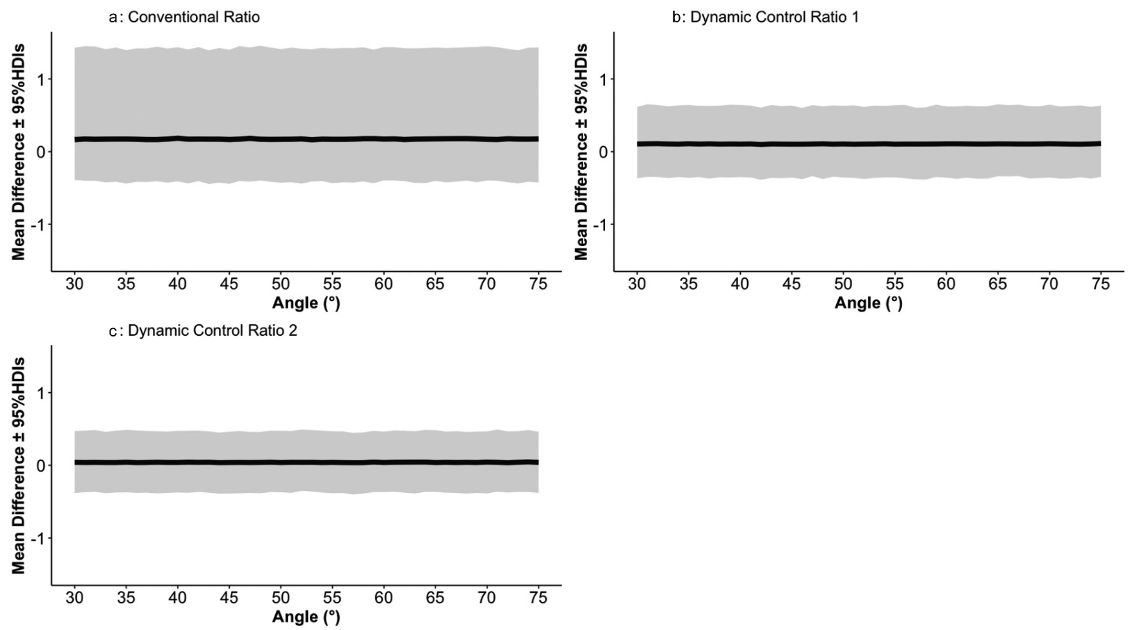

Figure 7. Illustrates the influence of soccer-specific exercise on the HDI of a difference for angle-specific strength ratios. Figure 7A illustrates the conventional strength ratio (conKF/conKE) at baseline and post exercise. Figure 7B illustrates the dynamic control ratio 1 (eccKF/conKE) at baseline and post exercise. Figure 7C illustrates the dynamic control ratio 1 (conKF/eccKE) at baseline and post exercise.

strength indices in amateur female soccer players. A secondary aim of the study was to present a novel female soccer-simulation that is based on the demands of female soccer-match play data. It was hypothesised that there would be reductions in angle-specific torques and ratios following a female soccer simulation. The findings of this study uniquely identified that AST of the concentric and eccentric knee flexors and extensors were lower following soccer-specific exercise when compared to baseline across all knee joint angles. The probability of a difference was increasingly uncertain for concentric actions (66–67%) compared to that of eccentric actions (77–78%). The reductions in eccentric strength of the thigh musculature may elevate injury risk, particularly for the knee flexors, which play an important role in decelerating the shank during the late swing phase of high-speed movements (Chumanov et al. 2012; Guex & Millet, 2013). Similarly, all three strength ratios were also lower after following soccer-specific exercise when compared to baseline across all knee joint angles, with $DCR1_{AST}$ demonstrating the largest reduction, but these findings have high uncertainty (58–66%). Reductions in strength ratios of the thigh musculature may also increase the risk of ACL injury, as the reduced capacity of the knee flexors to act as agonists for this ligament impairs their ability to counteract large anterior shear forces at the knee (Doorenbosch & Harlaar, 2003; Kellis et al., 2003). It must be noted that the probability of a difference greater than the CV+SWC was also 0% across all knee joint angles for all isokinetic strength outcome variables. These results may not be interpreted as practically meaningful changes since the present reductions in AST and DCR_{AST} in thigh musculature strength were lower than the variation of the isokinetic strength assessment combined with a smallest worthwhile change. These findings present observations into how thigh musculature strength responds to female soccer-specific exercise, and has implications for potential injury risk, performance and recovery from exercise that may inform subsequent exercise prescription.

The present study uniquely identified that reductions of thigh musculature strength in female soccer players are consistent across the torque-angle curve, with these reductions being greater for eccKE and eccKF following a novel female soccer simulation based on female match-play data. The greater reductions in eccKE and eccKF AST may be accounted by the mechanical demands of soccer-specific exercise, such as sprinting, high-speed running and change of direction tasks that are commonly performed (Horan et al., 2023; Mayhew et al., 2021). As the eccKF decelerate the shank during the late swing phase and early stance phase (Guex & Millet, 2013), and the eccKE resist external knee flexor moments during the eccentric phase (Norcross et al., 2013; Podraza & White, 2010) of sprinting, high-speed running and change of direction tasks (Horan et al., 2023; Mayhew et al., 2021), the higher muscle forces exhibited in eccentric actions when compared to isometric and concentric actions may account for the present observations. It must be noted that the present study, for all concentric and eccentric actions of the thigh musculature, that there is still uncertainty with these reductions in AST, particularly that the reductions in strength were always less than the coefficient of variation plus the smallest worthwhile change. Therefore, the observed reductions in AST of the present study may not be practically meaningful, but further research into female soccer-specific exercise responses of the thigh musculature and potential injury risk in female soccer players with reference to soccer-specific exercise is warranted.

The current evidence base is limited regarding the responses of thigh musculature strength following female soccer-specific exercise. Previous research in both female (Ferguson et al., 2023) and male (Field et al., 2022; Greig, 2008; Page & Greig, 2020; Small et al., 2010) soccer players identify the largest reductions are typically observed for eccKF. However, unlike the present study, these previous observations were focused on isokinetic peak torques, whereas the present study observes reductions in thigh musculature strength across the torque-angle curve, including at increased knee extensions angles where thigh musculature and knee ligament injuries are more likely to occur (della Villa et al., 2020; Lee et al., 2018; Lucarno et al., 2021). Angle-specific strength responses following soccer-specific exercise in female (Ferguson et al., 2023) and male (Page & Greig, 2020) soccer players is also sparse, but report reductions in eccKF at varying angular ranges (30–65° and 10–40° of knee flexion). These previous observations are not entirely in agreement with the present study since there was only 77–78% probability of a difference of baseline being higher when compared to post exercise, and that reductions in strength were lower than the variation of the isokinetic strength assessment combined with a smallest worthwhile change. These conflicting observations may be attributed to the statistical approaches adopted, with observations from previous literature performed separate inferential tests at each knee joint angle which would cause inflation of Type I errors (false positives) (Shreffler & Huecker 2020). It must also be noted that assessments of the eccKE were not conducted in research in both female and male soccer players. The novel inclusion of eccKE strength assessments in the present study have been particularly negated in the evidence base, and this may be important for injury risk given that these muscular actions are required to dissipate large impact forces and provide dynamic knee stability during utility movements commonly performed in soccer-match play and associated with injury risk (Norcross et al., 2013; Podraza & White, 2010). Future research should better consider the role of eccKE for knee stabilisation and the influence of fatigue on potential reduction of injury risk.

The findings of the present study also observed reductions in strength ratios, particularly the $DCR1_{AST}$, partially in agreement with previous research in both females (Ferguson et al., 2023) and males (Field et al., 2022; Greig, 2008; Small et al., 2010). Similar observations were also identified that $DCR1_{AST}$ with reductions in 10–40° of knee flexion in amateur female soccer players (Ferguson et al., 2023). The present study is not entirely in agreement with previous observations given the reductions in $DCR1_{AST}$ is uncertain (66%) and that reductions in strength were lower than the variation of the isokinetic strength assessment combined with a smallest worthwhile change, which is likely due to different statistical approaches adopted. Nevertheless, the reductions in $DCR1_{AST}$ may increase injury risk whereby there is a reduced capacity of the eccKF to counteract large anterior shear forces at the knee produced by the conKE during the late-swing phase and early stance phase of running and change of direction tasks (Chumanov et al., 2012). These present findings and those of literature are mainly attributed to reductions of eccKF, but with conKE being less effected. With that said, the present study does have some uncertainty with these observations, particularly for CR_{AST} and $DCR2_{AST}$. The uncertainty regarding CR_{AST} and $DCR2_{AST}$ is likely due to that conKE and conKF reduced at the same magnitude, thus preserving the same ratio. Future research must continue to identify how these musculature respond to soccer-specific exercise, with implications for injury risk. Additional research also needs to strengthen the link between thigh musculature strength ratios and injury risk in female soccer players. Given that the evidence base regarding isokinetic strength assessments and injury risk in female soccer players is extremely limited, studies that can provide normative data or values that indicate increased injury risk would help to provide more context into strength ratios and the responses following soccer-specific exercise.

Further research may wish to continue investigating isokinetic thigh musculature strength responses following the completion of the FEMS-90. Future research may wish to utilise the FEMS-90 to explore the impact of fatigue in female soccer players in other scenarios, such as periods of fixture congestion and extra-time. Given that there are biomechanical and neuromuscular contributors of injury risk in female soccer players, assessments of high-risk movement patterns related to thigh musculature and knee ligament injury risk can also be assessed following the completion of the FEMS-90. Practitioners can use the FEMS-90 to design evidence-based conditioning programs that help athletes maintain performance, reduce injury risk, assess readiness to return-to-play following injury and monitor recovery.

This study is not without limitations. The low testing velocity of $60°·s^{-1}$ may be viewed as a limitation given that injury typically occurs at much higher knee angular velocities (Chumanov et al., 2012; Guex & Millet, 2013). This limitation is due to equipment constraints of the IKD as it is not possible to obtain a true isokinetic phase at higher testing velocities and would not be able to capture data at increased knee extension where injury is more likely to occur (Guex & Millet, 2013; Hewett et al., 2009). Moreover, with the IKD sampling rate set at 100 hz, capturing data at precise knee joint angles may not be possible when using higher angular velocities. As a result, angle-specific data may be limited to slower testing velocities (e.g., $60°·s^{-1}$). The isokinetic strength assessments conducted in the present study also do not consider the rate muscle activation or force development and may also provide some unique insight into fatigue response given their relevance to injury. The present study also did not control for injuries sustained over 3 months at the time of data collection and must be considered a limitation. The present study also did not control for menstrual cycle, and the effect it has on isokinetic strength assessments in uncertain in angle-specific data is unknown despite previous observations suggesting no effect on peak torques (Gordon et al., 2013; Gür et al., 1999). Given that thigh musculature strains and knee ligament injuries are suggested to more likely occur at the dominant and non-dominant

limbs, respectively (Hägglund & Waldén, 2016; Le Gall et al., 2008), future research may also need to consider how bilateral strength differences are influenced by soccer-specific exercise in female soccer players. Moreover, given the absence of normative data or reference values regarding isokinetic strength assessments in female soccer players, future research is required to help provide more context into strength ratios in relation to injury risk, and the responses following soccer-specific exercise. Regarding the FEMS-90, this exercise does not include kicking or jumping activities, meaning that the simulation may not fully represent the biomechanical demands of female soccer match-play. Moreover, the responses from the FEMS-90 may not elicit the same biomechanical demands when compared to match-play, meaning that the present responses could be lower to that of female soccer match-play. Given that the present study were in amateur female soccer players, and that the FEMS-90 was developed using professional female data, the present findings may also be heightened.

Conclusion

The findings of this study uniquely identified that AST and strength ratios of the concentric and eccentric knee flexors and extensors were lower following soccer-specific exercise for all knee joint angles, but these differences should be interpreted with caution given the uncertainty between baseline and post exercise measures. This study achieves its primary aim by quantifying acute changes in thigh musculature strength indices in response to a novel female soccer simulation. Additionally, the secondary aim was addressed by implementing a novel simulation based on the demands of female soccer match play and is the first study to present a female soccer simulation based on the demands of female match-play. These findings contribute to understanding how thigh musculature strength responds to soccer-specific exercise and have implications for managing injury risk, enhancing performance and optimising recovery in female soccer players. Future research should further investigate the relationships between soccer-specific exercise, strength changes and injury risk markers in female soccer players to refine injury prevention and training protocols.

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