LOWER BODY STIFFNESS VARIATIONS AND ASSOCIATED INJURY RISK DURING SPORTS SPECIFIC TASKS

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The purpose of this study was to evaluate the longitudinal stiffness changes and associated prospective lower limb injury risk across a season of training in female athletes. Thirty-nine high level female athletes from varied training backgrounds completed sports-specific tasks and repetitive hopping. Repeated measures analysis of variance, independent t-tests, receiver operating characteristics curves and logistic regression analysis were implemented to evaluate the identified aims of this study. Results suggest athletic training influences longitudinal changes in leg stiffness which may place athletes at increased injury risk. An optimal range of stiffness may exist allowing optimal performance and minimised injury risk.

KEYWORDS: athletic training, injury prediction, screening tools, female

INTRODUCTION: Lower limb stiffness quantifies the relationship between the amount of leg flexion and the applied external load (Butler, Crowell & Davis, 2003). Research has established that stiffness is linked to both performance and injury risk (Butler et al., 2003; Watsford et al., 2010), with higher levels of stiffness associated with increased overuse injury risk and lower levels of stiffness related to increased soft tissue injury risk (Butler et al., 2003). Athletic training may develop key lower limb and joint stiffness modulation mechanisms such as neuromuscular control (Butler et al., 2003). Hence an optimal range of lower limb stiffness may exist, enabling maximal performance whilst minimising injury risk, however this remains unknown. Few studies have evaluated longitudinal leg stiffness to gain an understanding of the stiffness changes across a training season. Additionally, studies which have assessed longitudinal changes have utilised repetitive hopping tasks, predominately in male populations (Pruyn et al., 2013; Watsford et al., 2010). Although repetitive hop tasks are simple and cost-effective, these tasks may not adequately reflect leg stiffness during training and competition (Millett, Moresi, Watsford, Taylor & Greene, 2015). Lower limb stiffness monitoring has the potential for early injury risk identification and prevention potentially reducing lost training days. Thus, the purpose of this study was; 1) to investigate the longitudinal differences across a season of training (pre, post and off-season) in leg stiffness (K_{leg}) in different female sub-populations from varied training backgrounds during repeated hopping and sports-specific tasks, and 2) to prospectively evaluate the associated lower-body injury risk to athletes.

METHODS: Thirty-nine female participants from varying athletic backgrounds (15 nationally identified netballers, 12 high level endurance athletes and 12 age matched controls) were recruited and provided written informed consent (Table 1). Testing procedures were approved by the Human Research Ethics Committee of the Australian Catholic Universities. Netball athletes represented a high intensity intermittent sport involving maximal jumping efforts, explosive sprints and change of direction, while endurance athletes (1500 m – marathon) represented a sport requiring continuous, efficient running at submaximal intensities. Control group participants did not exceed four hours of weekly physical activity.

Table 1- Participant Descriptive Information. Values: mean (SD).

Group	N	Age (Years)	Mass (kg)	Height (cm)	Average Training Hours ($h \cdot wk^{-1}$)	Training Years
Netball	15	16.8(1.0)	70.7(5.8)	178.0(5.8)	5.8(2.4)	4.1(2.2)
Endurance	12	19.8(4.2)	53.2(3.0)	166.3(4.8)	10.3(3.4)	7.8(2.4)
Control	12	22.3(2.3)	59.2(10.7)	163.1(5.9)	1.9(1.1)	-

Participants attended three testing sessions across a training cycle; pre-season, post-season and off-season. During each session, following familiarisation trials, participants completed five trials of two sports-specific tasks at their event specific competition pace (a 50m sprint and an anticipated change of direction cutting task) and one trial of 27 repetitive hops at submaximal intensity (indicated by a target height set at 70% of maximal CMJ height). Research indicates spring-mass characteristics are present at equivalent running velocities within similar athletic populations (Clark & Weyand, 2014). All tasks were performed on the participant's dominant leg. Data was captured using a 10 camera motion analysis system (Vicon MX; Oxford Metrics Ltd., Oxford, United Kingdom; 500 Hz) and force plate (Kistler, 9281CA, Switzerland; 1000 Hz). Kinematic data was filtered using a low pass Butterworth dual-pass fourth order filter with the cut off frequencies set at 16 Hz (jump data) and 23 Hz (running tasks) (Winter, 2005). K_{leg} was determined using the McMahon and Cheng (1990, as cited in Butler & Crowell, 2003) formula. Within lab testing indicates intra-session K_{leg} reliability for these assessed tasks (ICC: 0.95-0.98; CV: 5.6-8.2%). K_{leg} measures were normalized to body mass and standardized to the pre-season horizontal touchdown velocity or jump frequency using residual calculations derived from population specific linear regression analysis. The highest and lowest K_{leg} scores of the five trials were excluded with the remaining trials averaged for the sprint and cutting task. The first five and last two contacts during the repetitive hopping task were excluded with the mean of the remaining trials utilised in subsequent analysis. Sports-related, lower-body, non-contact injuries that occurred during the tracking period were recorded using a self-reported questionnaire. Netball and endurance athletes were pooled for injury analysis with injuries categorised as either; 1) soft tissue and, 2) overuse (Sports Medicine Australia, 2010). The theoretical model suggests the absolute stiffness value is key to injury risk identification, equality was established between netball and endurance injury K_{leg} scores. Data was assessed for normality utilising a critical appraisal approach (Peat & Barton, 2006). Repeated measures analysis of variance with Bonferroni post-hoc tests or the non-parametric equivalent Friedman test evaluated longitudinal K_{leg} changes within each athletic population, injured and uninjured groups. Additionally, independent t-tests or the non-parametric equivalent Mann-Whitney U tests assessed K_{leg} differences between injury groups within each testing phase. Receiver operating characteristic (ROC) curves determined a critical K_{leg} cut off threshold for subsequent lower limb injury, overuse injury and soft tissue injury risk prediction using logistic regression. All statistical analysis was undertaken using SPSS® (v21.0, IBM, NY, USA) with an alpha level set at $p < 0.05$. P values with the range of 0.05-0.09 with an effect size greater than 0.50 were defined as providing a clinically meaningful relationship (Peat & Barton, 2006).

RESULTS AND DISCUSSION: No longitudinal K_{leg} changes were observed within the control group across any assessed tasks. Netballers displayed a significant decline in K_{leg} in sprinting from pre to off-season (p=0.005) and a clinically meaningful decline in K_{leg} between post and off-season measures (p=0.071, ES: -0.83). Lower K_{leg} values possibly reflect reduced strength and adaptations to performance demands following a period of reduced match-play and general conditioning. In contrast, during the anticipated sidestep cutting task netball athletes significantly increased K_{leg} from post to off-season (p=0.021) with no change observed between pre and post-season measures (p=1.000). Research has suggested reduced leg stiffness may be more effective during high impact reactive tasks (Walshe & Wilson, 1997). It is speculated this may be the case for netballers where lower K_{leg} is necessary to perform a controlled landing and sidestep at higher running velocities. Thus following a period of reduced match play, increased K_{leg} may be a response to lessened exposure to high velocity rotational movements and increased need for general aerobic fitness. Endurance athletes exhibited significantly higher sprint post-season K_{leg} scores when compared to off-season (p=0.021). Maintaining a high level of K_{leg} through the competition phase of training (pre to post season) is critical for this population to meet performance demands, with higher K_{leg} believed beneficial for optimal performance and running economy (Butler et al., 2003). However, higher K_{leg} may increase overuse high impact injury (Butler et al., 2003) which appears reflected in the high overuse injury rate reported by endurance athletes across the season. During the anticipated sidestep cutting task endurance athletes tended to reduce K_{leg} in post (p=0.083, ES: -0.26) and off-season (p=0.083, ES: -0.77) when compared to the pre-season scores. As this population rarely performs high velocity change of direction tasks, it's suggested that seasonal variations may not reflect athletic training, but are an inherent response to a lack of muscular adaptations necessary to meet performance demands. While the repetitive hopping K_{leg} scores of all groups elicited similar patterns between the testing phases as the sport-specific tasks, no significant differences were observed. These results were in line with previous research (Pruyn et al., 2013), where hopping did not elicit longitudinal K_{leg} changes across a training season. It is suggested that repetitive hopping may not require sufficient performance demands to induce the same stiffness responses as sports-specific tasks (Millett et al., 2015). Highlighting the need to take an athlete's training background into consideration when identifying screening tools to assess K_{leg} of athletes.

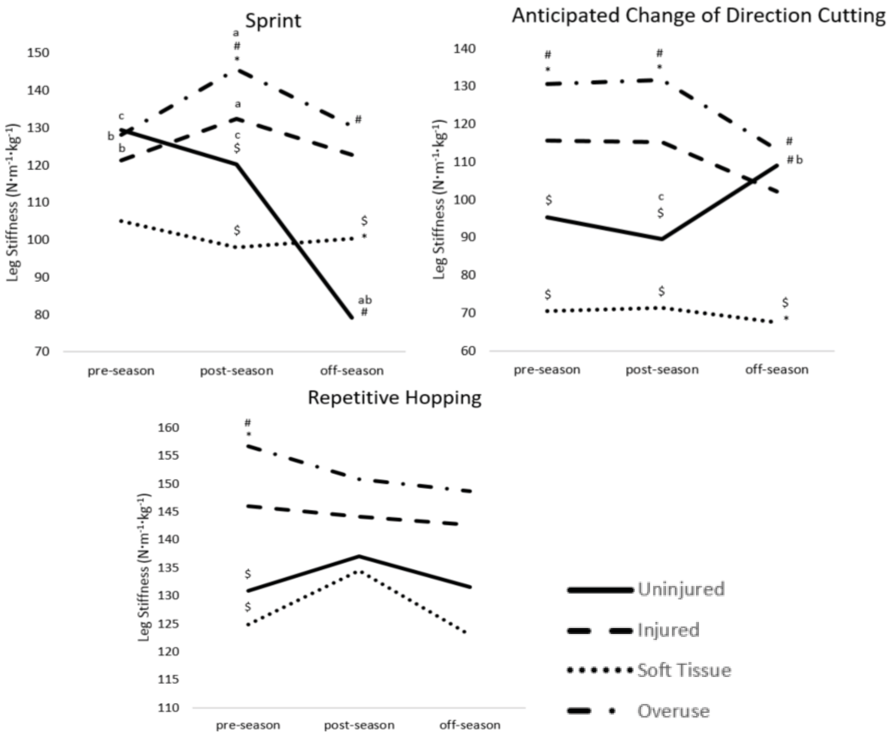

Figure 1- K_{leg} changes in uninjured and injured groups across a season of training and within individual testing phases (pre, post and off-season). ^{a} Significantly different to pre-season; ^{b} Significantly different to post-season; ^{c} Significantly different to off-season; * Significantly different to uninjured; ** Significantly different to injured; $^\#$ Significantly different to soft tissue; $^\$$ Significantly different to overuse.

Injury analysis revealed 63.0% of athletes reported a sport-related lower limb injury during the study. The majority of injuries (83.3%) occurred during the competition phase i.e. between the pre and post-season testing sessions. Within the netball group, 60.0% presented with an injury during the competition season, of these 63.6% were soft tissue, while 36.4% were overuse injuries. Injury incidence in the endurance group revealed 66.7% presented with an injury with 100% of these overuse injuries. Given potential bias due to high injury incidence classification differences within each group, additional analyses were undertaken to assess seasonal stiffness changes across the injury classification groups.

In line with previous research and the theoretical model, athletes who presented with soft tissue injuries displayed significantly lower K_{leg} scores while the overuse injury group displayed significantly higher post-season K_{leg} (p=0.021)(Butler et al., 2003). It's suggested that K_{leg} increases across a season may increase an athletes' exposure to greater forces and mechanical loading, thus increasing the lower limb stress application leading to potential overuse injury risk (Butler et al., 2003). The uninjured group displayed K_{leg} scores in between the soft tissue and overuse injury groups across all tasks, significant and clinically meaningful differences suggest an optimal band range of K_{leg} may exist (Figure 1)(*Sprint:* pre-season soft tissue lower K_{leg} than uninjured p=0.092, ES=1.42 and overuse p=0.073, ES=1.25; post-season sprint overuse significantly higher K_{leg} than uninjured p=0.042 and soft-tissue 0.003, soft tissue lower K_{leg} than uninjured p=0.076, ES=1.30. *Anticipated sidestep cutting:* overuse significantly higher pre + post-season K_{leg} than uninjured p=0.041, p=0.010 and soft tissue p=0.006, p=0.002; uninjured higher post season K_{leg} than soft tissue p=0.076, ES=1.15). These results suggest K_{leg} scores outside this optimal range which may not shift or lower through a period of increased training load and intensity may increase an individual's likelihood of injury, with lower K_{leg} leading to soft tissue injuries and higher K_{leg} levels resulting in overuse injuries. This is further highlighted by seasonal K_{leg} changes where no significant change was evident in K_{leg} in all tasks for the soft tissue group and a significant increase was observed in K_{leg} pre to post-season in the overuse group during sprinting (p=0.021). Thus, athlete training load and K_{leg} monitoring may be important in athlete injury prevention however these relationships require further investigation. Whilst repetitive hopping was able to identify differences between the injury groups at a given time point (pre-season overuse significantly higher K_{leg} than uninjured p=0.029 and soft tissue p=0.015; post season soft tissue lower K_{leg} than overuse p=0.090, ES=1.49), it was unable to identify changes across the season. Thus, the repeat hopping task may not be able to induce the same performance or loading demands as sports-specific tasks.

ROC curve and logistic regression results emphasised the need for practitioners to consider the relevance of the task to the habitual training background of the athletes. When all injury types were pooled across both athletic groups the results appeared confounded due to the nature of injuries differences, highlighting the need to treat injury prediction models for soft tissue and overuse separately. Pre-season K_{leg} in netball athletes during sprints, anticipated change of direction and repetitive hopping tasks appeared to adequately discriminate athletes who presented with soft tissue (80%) and overuse injuries (75-100%) and also displayed sufficient specificity in predicting uninjured athletes (70-81.8%). Pre-season K_{leg} in endurance athletes during sprints sufficiently predicted overuse injuries (87.5%), while it appeared poor in its specificity to differentiate uninjured athletes (50%). It is important to note the proportion of overuse injuries and limited uninjured athletes within this cohort which may influence these results. The anticipated change of direction cutting task was poor in distinguishing injury risk within endurance athletes, likely due to their unfamiliarity with the task. The repetitive hopping task appears to serve as an 'intermediate' task for monitoring athletic populations. Whilst the present study is novel in assessing longitudinal changes and associated injury risk, it is limited to testing at isolated time points. Further research should explore methods to monitor K_{leg} in the daily training environment to adequately assess ongoing stiffness fluctuations, training load responses and injury risk.

CONCLUSION: Chronic athletic training appears to influence longitudinal variations in K_{leg} within athletic populations during sports-specific tasks. An optimal range of K_{leg} may exist allowing optimal performance whilst minimising injury risk. An athlete's training background may influence the appropriateness of tasks in observing longitudinal K_{leg} changes and predicting associated injury risk. The results provide practical insight into the importance for practitioners, coaches and researchers in considering sports-specific tests in K_{leg} assessment. Repetitive hopping may serve as an 'intermediate tool' however care needs to be taken in the interpretation of results. Pre-season screening identifying potentially high K_{leg} and low K_{leg} 'at risk' athletes which may enable coaches and sport scientists to modify training load, recovery practices and implement ongoing athlete monitoring to reduce the risk of injury and subsequent training days lost enhancing preparedness for competition.

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