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LEG STIFFNESS IN FEMALE SOCCER PLAYERS: INTER-SESSION RELIABILITY AND THE FATIGUING EFFECTS OF SOCCER-SPECIFIC EXERCISE

ABSTRACT

Low levels of leg stiffness and reduced leg stiffness when fatigue is present compromise physical performance and increase injury risk. The purpose of this study was to (a) determine the reliability of leg stiffness measures obtained from contact mat data and (b) explore age-related differences in leg stiffness following exposure to a soccer-specific fatigue protocol in young female soccer players. 37 uninjured female youth soccer players divided into 3 sub-groups based on chronological age (U13, U15 and U17 year olds) volunteered to participate in the study. Following baseline data collection during which relative leg stiffness, contact time, flight time was collected, participants completed an age-appropriate soccer-specific fatigue protocol (SAFT[90]). Upon completion of the fatigue protocol, subjects were immediately re-tested. Inter-session reliability was acceptable and could be considered capable of detecting worthwhile changes in performance. Results showed that leg stiffness decreased in the U13 year olds, was maintained in the U15 age group and increased in the U17 players. Contact times and flight times did not change in the U13 and U15 year olds, but significantly decreased and increased respectively in the U17 age group. The data suggests that age-related changes in the neuromuscular control of leg stiffness are present in youth female soccer players. Practitioners should be aware of these discrepancies in neuromuscular responses to soccer-specific fatigue, and should tailor training programs to meet the needs of individuals which may subsequently enhance performance and reduce injury risk.

KEY WORDS: youth, maturation, neuromuscular, SAFT[90]

INTRODUCTION

The stretch-shortening cycle (SSC) is defined as a muscle action that involves pre-activation of the muscle prior to ground contact, a fast eccentric action, and a rapid transition between the eccentric and concentric phases [16]. Throughout a soccer match, players routinely utilize SSC actions, especially in high-intensity movements that require high levels of rate of force development (RFD), such as maximal velocity running and jumping.

Leg stiffness is commonly used as a measure to characterize SSC function, and represents the ratio between peak vertical ground reaction forces and peak center of mass displacement during ground contact [20]. Comprising stiffness regulation around all the joints of the lower limb, this metric functionally represents how individuals have to control multi-joint movements during SSC exercise [16] and is regulated by feed-forward and feedback neural mechanisms, which appear to develop from childhood into adulthood [18, 25]. Low levels of leg stiffness compromise physical performance and are well related to sprinting and jumping performance [20, 24]. Despite this there are limited studies examining changes in leg stiffness during childhood in females, which is surprising given that leg stiffness also plays an important role in the dynamic stability of the knee. Given that young females are a high risk group for knee injuries understanding changes in stiffness during growth and maturation are essential in helping to develop appropriate prevention strategies [1, 23].

Previous research has identified that fatigue is a significant contributor to reduced lower limb dynamic knee stability, which may increase the risk of non-contact ACL injury [19]. A recent review by Ratel and Martin [29] suggest that there may be a progressive withdrawal of physiological protection against high intensity exercise

induced fatigue during puberty. However, the authors are cautious as they conclude that the effects of fatigue on neuromuscular function during adolescence has scarcely been studied, despite this knowledge being able to contribute to the management of training load and recovery in maturing children [29].

McLean and colleagues [19] reported that the repeated nature of stretch loadings during prolonged exercise may lead to modified musculotendon unit behavior, altered stiffness regulation and overall impaired SSC function. Fatigue related reductions in leg stiffness indicate compromised neuromuscular control and increased injury risk. However, adult studies have provided conflicting results with some studies showing an increase in stiffness after fatigue [22], some showing a decrease [9] and some showing no change [12]. It is difficult to attribute these findings to mechanistic structures but they could be influenced by the nature of the fatigue protocol, and the methods used to calculate leg stiffness. There appears to be only one previous study exploring the effects of soccer match fatigue on leg stiffness in male youth players [24]. Oliver et al's [24] study showed an individualized response in stiffness and any change in stiffness was attributed to changes in pre-activation. For those who demonstrated reduced leg stiffness this was due to changes in centre of mass displacement as opposed to alterations to peak GRF, suggesting a more of a yielding action during the ground contact phase. However, this study was in only one age group of boys and thus there is a need for research in girls across maturity, particularly as girls experience changes which may contribute to altered stiffness and increased injury risk with maturation.

Whilst the effects of maturation on landing strategies in young female athletes has previously been observed [11], existing research has not yet examined the interaction between maturation and fatigue on leg stiffness. Therefore, it is still unclear how the regulation of SSC functions in response to fatigue-inducing exercise changes

at different stages of growth and development and subsequently what prevention strategies are needed to reduce injury risk. Therefore the aim of this study was to investigate: a) the intersession reliability of leg stiffness in female youth; b) the influence of soccer-specific fatigue on measures of leg stiffness in U13, U15 and U17 year-old female players.

METHODS

Experimental approach to the Problem

A between-group, repeated measures design was used to examine the effect of a soccer-specific fatigue protocol on leg stiffness in young female soccer players. Leg stiffness was the dependent variable, while chronological age served as an independent variable to determine if any changes in leg stiffness to the fatigue protocol were age-related. Data were collected from a mobile contact mat, and measures of leg stiffness were calculated based upon contact time, flight time, and jump height data.

Subjects

36 females aged 12-18 y from an FA Women's Super League Team professional youth academy were recruited to participate in this study. Players in each squad were recruited from three age groups U13's (n = 14), U15's (n = 9) and U17's (n = 13). Participant characteristics for each age group are presented in Table 1. Participants were initially grouped according to chronological age; however, these groupings did not change when maturation was considered. Exclusion criteria for the study included: (i) history of orthopedic problems, such as episodes of hamstrings or knee injuries, fractures, surgery or pain in the spine or hamstring muscles over the past six months; or (ii) self-reported presence of delayed onset muscle soreness (DOMS) at a given testing session. Testing

occurred three months into the competitive season and all players had a minimum training age of three years. Players trained for 4-6hrs weekly and would normally compete in one competitive match. No participant was engaged in any formalized strength and conditioning program prior to the testing period. Participants were asked to avoid their regular training regimen during the testing period, and to refrain from vigorous physical activity 48 hours prior to testing. Testing occurred a minimum of 48hr after a competitive match or training session to reduce the effects of residual fatigue. The project received ethical approval from the University's Research Ethics committee, and both written participant assent and parental consent were obtained prior to testing. Written informed consent was obtained from the club prior to the recruitment of participants.

*****Table 1 near here*****

Procedures

Maturational Status. Biological maturity was assessed non-invasively by incorporating measures of body mass, standing height and stature into a regression equation to calculate the age from peak height velocity (PHV) [21].

Leg Stiffness. For the reliability study a total of 4 test sessions were undertaken with the first 2 sessions classified as habituation/familiarization sessions. The test-retest sessions were separated by 7 days. Leg stiffness was calculated from contact time data obtained during a sub-maximal hopping protocol [17] immediately prior to and following the simulated soccer-specific fatigue protocol. The coefficient of variation for leg

stiffness estimated using the above methods with male youths has been reported to be 10.2% [17]. In the current study the procedures were repeated for two trials and an average stiffness value reported. This will improve the reliability by a factor of $1/\sqrt{2}$ [28], giving an adjusted coefficient of variation of 7.2%. For each trial, participants were instructed to perform 20 consecutive hops on top of a mobile contact mat (Smartjump, Fusion Sport, Australia) at a frequency of 2.5 Hz, with data collected instantaneously via a hand-held PDA (iPAQ, Hewlett Packard, USA). This frequency was selected to ensure movement patterns were reflective of typical spring-mass model behavior [17]. Hopping frequency was maintained via an audio signal from a quartz metronome (SQ-44, Seiko, UK). Participants were instructed to keep hands on the hips at all times to avoid upper body interference; jump and land on the same spot; land with legs fully extended and to look forward at a fixed position to aid balance maintenance [17]. Absolute leg stiffness ($kN \cdot m^{-1}$) was calculated using the equation proposed by Dalleau et al. [7] (equation 2), where K_N refers to leg stiffness, M is the total body mass, T_c is equal to ground contact time, and T_f represents the flight time. The equation has been shown to possess acceptable validity and reliability when used in pediatric populations [17].

$$\text{Leg stiffness} = [M*\pi(T_f+T_c)]/T_c^2[(T_f+T_c/\pi)-(T_c/4)] \qquad \text{[equation 2]}$$

Due to the close association between body mass and leg stiffness and the influence of leg length on mechanical properties of human locomotion, measures of absolute leg stiffness were divided by body mass and limb length to provide a dimensionless value of relative leg stiffness [20]. The method of estimating leg stiffness

has been found to be valid in adolescent children, with a typical error of estimate (TEE) of 7.5% (5.6-11.3) at a frequency of 2.5 Hz [17]. .

Soccer-specific fatigue protocol. Following the completion of the sub-maximal hopping test in a non-fatigued state, participants completed a standardized warm-up inclusive of sub-maximal activity and dynamic mobility drills. On completion of the warm-up, participants were instructed to commence the soccer-specific aerobic field test (SAFT[90]) protocol [33]. The SAFT[90] requires participants to perform a combination of multidirectional movements including forwards and backwards walking, jogging and sprinting, lateral side-stepping, and acceleration and deceleration where necessary to navigate around the 20 m shuttle run course inclusive of strategically positioned poles to simulate the demands of the competitive match play [33]. The intensity and form of activity was determined by a pre-recorded 15 minute activity protocol which was verbally projected from an audio CD. In order to replicate the demands of competitive match play, the 15 minute activity protocol was repeated randomly and intermittently for a duration that was indicative of age group-specific match play volumes (U13 = 60 mins (4 x 15 min intervals); U15 = 80 mins (2 x 40 min intervals); U17 = 90 mins (2 x 45 min intervals), inclusive of the passive rest periods experienced at intervals within the game (U13 = 2 mins; U15 = 10 mins; U17 = 15 mins). These durations were selected in order to match the typical activity loads experienced by players within each age group.

Statistical Analyses

To determine inter-session reliability, a series of paired samples t-tests were used with a *p* value ≤ 0.05 indicative of a significant difference between the two tests. Within-

subject variation was determined using mean coefficients of variation (CV %). Further reliability statistics included: change in mean and inter-class correlation coefficient (ICC).

Descriptive statistics (means ± *sd*) were calculated for all performance variables for both pre-training and post-training intervention data. Inferential statistics were also used to examine the meaning of differences in leg stiffness following the SAFT[90] intervention between U13, U15 and U17 age groups. The smallest worthwhile effect was used to determine whether the observed changes were considered negative, trivial or positive. The smallest worthwhile effect was calculated as 0.20 of the pooled between-group standard deviation pre-training [2]. A 90% confidence interval was applied to the between-group difference to calculate the probabilistic inference of each observed difference being greater than the smallest worthwhile effect, applying thresholds of 25-75% as possibly, 75-95% as likely, 95-99.5% as very likely and >99.5% as almost certainly [15]. The outcome was deemed unclear when the 90% confidence interval of the mean change overlapped both positive and negative outcomes, otherwise the outcome was clear and inference reported as the category (negative, trivial or positive) where the greatest probability was observed. All statistical analyses were computed via SPSS® V.20 for Windows.

RESULTS

Participant characteristics can be seen in table 1.

Table 1 Here

Paired samples t-tests showed no significant differences between test sessions for any age group. ICCs and CVs were 0.78 and 8.2%, 0.91 and 9.8%, 0.71 and 9.7% for the U13, U15 and U17 age groups respectively (Table 2).

Table 2 Here

The U13 completed an average of 6.3 ± 0.7km, the U15 10.5 ± 0.6km and the U17 10.6 ± 0.7km during the football specific fatigue trial. Relative changes and qualitative outcomes resulting from the within group analysis are presented in figure 1. The fatigue effects on relative leg stiffness were 'possibly negative' for U13s, 'unclear' in the U15s and 'very likely positive' in the U17s. Most participants' stiffness decreased in the U13 age group (n=10) but a few did increase their stiffness (n=4). There was an individualized response to fatigue in the U15 age group with four participants increasing and five participants decreasing leg stiffness. All girls in the U17 age group increased stiffness post fatigue.

Figure 1 Here

DISCUSSION

This study examined between session reliability and the effects of a soccer-specific fatigue protocol on leg stiffness in female youth soccer players. The reliability data demonstrated that mobile contact mats produce reliable results with a youth female population as no statistically significant difference was found between testing sessions, moderate to high ICCs were recorded (0.75-0.91) and the CV for each age group was <10%. These findings are in agreement with the one previous study examining the reliability of leg stiffness using the same equipment with 13y-old male participants[17]. These values are below the 10% cut-off which has been deemed to be a measure of modest reliability (CV<10%)[4, 6]. The modest reliability found in the current study

adds further support to the use of mobile contacts mats in female youth athletes. Due to the portability of equipment, the low physical demands of submaximal hopping, and the simplicity of testing supports their use in the field to determine leg stiffness in female youth athletes.

The main finding of the study was that age dependent effects were evident in leg stiffness data when fatigue was present. The youngest age group (U13) showed a decrease in leg stiffness which was 'possibly negative', changes in the U15 age group were 'unclear', whilst the oldest players (U17) showed a change in leg stiffness post fatigue which was 'very likely positive'. These results suggest that football specific fatigue induces an inhibitory response in younger pre-pubertal players, no effect in pubertal individuals, and a heightened response in post-pubescent players. These neuromuscular differences between age/maturation groups indicate that unique mechanisms associated with different stages of development are present in young female soccer players when fatigue is present. Importantly these finding suggest that there is not a progressive withdrawal of a physiological protection to fatigue during adolescence, as previously suggested [29], albeit not in well trained female youth. Indeed, our findings appear to indicate an enhancement in fatigue resistance through adolescence that might be attributed to training age and physiological adaptation through appropriate loading.

A reduction in leg stiffness was evident in the youngest age group (U13) only. Leg stiffness is governed in part by pre-activation and short-latency stretch reflexes [14]; with up to 97% of the variance in leg stiffness explained by the contribution of pre-activation and stretch-reflex response of lower limb extensor muscles [25], from a neuromuscular perspective, it is likely that fatigue will have induced a change in the activation of the musculotendon unit. Such changes are

typically characterized by a reduction in pre-activation prior to ground contact (feed-forward control) and an increase in co-contraction after ground contact (feedback control), and this strategy has been shown to be more pronounced in pre-pubertal children than adults [5]. Others have also indicated a strong relationship between changes in leg stiffness and background neuromuscular activity (preactivation) in male youth soccer players following simulated soccer performance [24]. Confirming this, preparatory co-contraction ratios have been reported as 2 times higher in adults compared to children[31]; changes in stiffness are likely to reflect changes in these control mechanisms. Furthermore, recent data has shown that pre-pubertal children demonstrate higher central fatigue than adults during repeated maximal contractions [30]. In response to fatigue, more compliant tendinous structures and reductions in motor unit recruitment in younger children may serve to protect the muscle from undue damage and biological harm [13, 33].

Results from the current study demonstrate that players within the U15 age group were able to maintain lower limb stiffness following the fatigue protocol. This finding is in agreement with recently published research that examined the effects of a simulated soccer match on vertical stiffness [3]. In this study, Cone and colleagues [3] highlighted that despite reductions in cutting and running speed, participants were able to maintain vertical stiffness. However, this was achieved via increases in vertical ground reaction forces and decreases in center of mass displacement, thus suggesting potential alterations in neuromuscular control in order to maintain overall leg stiffness. Oliver et al. [24] also reported no group related response to simulated soccer match play in 15y-old boys. While the current study did not directly measure force-time characteristics, analysis revealed that contact times and flight times of the U15s did not show any significant decrements following the fatigue protocol. Therefore, it could be

suggested that the U15 age group were able to maintain force producing qualities without an increased yielding effect. Mechanistically, this suggests that the U15 players suffered less peripheral or central fatigue in response to the SAFT[90], thus they were able to maintain neural drive to the activated motor units.

The observed increase in leg stiffness in the U17s suggests that the participants within this group altered their lower limb mechanics to enhance their rebounding qualities after the soccer specific protocol. Specifically, the current study showed a significant reduction in contact time and an increase in flight time, which suggests that the players were able to rebound higher in a shorter space of time. These findings were somewhat surprising, however a plausible explanation is that moderate fatigue was experienced by the U17 group during the SAFT90 which may have actually potentiated the active musculature, driven by enhanced motor unit recruitment, excitation and/or synergist activation [8]. Data from distances covered during the fatigue protocol show that the U17 completed a similar distance as the U15 group, despite the protocol being 10 minutes longer, suggesting insufficient activity to elicit exhaustive fatigue. The findings of the current study seem to indicate that any change in stiffness is a function of initial stiffness, as the U17 had the lowest initial stiffness values. Previous studies have suggested that lower musculo-tendinous stiffness could serve as a 'mechanical buffer' during repeated muscle actions which would limit the development of fatigue [ratel]. It is possible that those individuals with a high initial stiffness may have faster contraction times when running, thus having greater ATP turnover, eventually resulting in greater fatigue related responses. It is difficult to ascertain why the older girls have a lower baseline stiffness value but it may be due to the use of relative and not absolute values as taller/heavier older girls have lower

relative values. It is also possible that the older girls may be able to maintain contractile function of the muscle-tendon complex following loading from simulated match-play due to training and conditioned age.

An alternate hypothesis is that the induced fatigue in the U17 age group could have resulted in a change in the control strategy used to maintain leg stiffness. Previous data has indicated that under conditions of fatigue, adult females adopt an ankle-dominant strategy [27]. Specifically, it was reported that activation of the gastrocnemius and soleus increased, whereas, hamstring activation reduced and these alterations in neuromuscular control may increase the risk of injury. The gastrocnemius is an antagonist to the anterior cruciate ligament injury (ACL), particularly when the knee is in a near extended position [10]. Co-contraction of the gastrocnemius in concert with the quadriceps was also shown to further increase the strain on the ACL [10]. A move to an ankle dominant strategy may also mean that the U17 are benefiting from a stiffer Achilles tendon (undergoing a substantial pre-stretch), and this additional use of tendon stiffness would lead to less decrement in contractile-unit performance.

A limitation of this study is that force-time data were not collected to calculate leg stiffness. However, the use of mobile contact mats to calculate leg stiffness has previously been validated and deemed reliable in pediatric populations [17], and has shown to be sensitive in detecting the presence of accumulated fatigue[24]. The current study quantified leg stiffness as the mean of the best two trials, as opposed to one trials in previous research [17], to give an overall mean CV of 7.2%. Consequently, while the percentage changes for the U13 and U15 age groups were still less than the noise associated with the measurement tool, the change in performance for the U17 age group (12.3%) and the relative percentage change in the U17 compared to the U13s (17.2%) were clearly greater than the typical error (7.2%). Thus, caution should be

applied when analyzing the minimal performance changes in the younger cohorts; however, greater confidence can be attributed to the performance change in the older participants.

PRACTICAL APPLICATIONS

This study has identified three important considerations in terms of leg stiffness 1) Initial low leg stiffness is sub-optimal in older girls and thus influence physical performance; 2) Leg stiffness that reduces with fatigue is indicative of negative alterations in neuromuscular control and may be an injury risk; 3) Initial stiffness and changes in stiffness following soccer interact with maturation in young female players. Owing to well established association between reduced knee stability and increased risk of ACL injury in young females, practitioners should be aware of these age-related discrepancies in neuromuscular responses to soccer-specific fatigue, and should tailor training programs to meet the needs of individuals. Coaches should also consider screening leg stiffness in both a non-fatigued and fatigued state. Although injury risk may be heightened in older athletes, a recent meta-analysis identified an age-related association between neuromuscular training implementation and reduction of ACL incidence, demonstrating that earlier intervention was more effective in reducing injury risk [23]. Given the results of the current study, it is recommended that appropriate strength and conditioning programs are introduced to youth at the earliest possible opportunity to protect against the fatigue-mediated injury risk increase. These programs should include exercises targeted at fast-SSC actions, that include high movement velocities, high RFD, and short ground contact times. These exercises should be incorporated within a well-rounded training programme that also develops important physical qualities such as strength, motor skills and agility. Due to the reduced baseline

lower limb stiffness present within the U17 players; it is imperative that engagement with such programs is viewed as a long-term initiative to offset the increases in neuromuscular and biomechanical risk factors experienced from puberty. Our data indicates that training load, in particular recovery duration between sets or repeated high intensity exercise, does not need to be increased during the transition from childhood to adolescence, as fatigue does not compromise SSC capability in adolescence.

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Table 1. Participant characteristics per age group (mean $\pm$ *SD*)

	Under 13 (n = 14)	Under 15 (n = 9)	Under 17 (n = 14)
Age (years)	12.1 ± 0.5^{a}	13.9 ± 0.6	15.8 ± 0.5
Stature (cm)	146 ± 6^{a}	159 ± 8	166 ± 6
Body mass (kg)	40.8 ± 6.7^{a}	51.9 ± 8.8	61.9 ± 8.2
Leg Length (cm)	68.6 ± 3.4^{a}	73.4 ± 3.8	79.8 ± 3.8
PHV Maturity offset (years)	-0.28 ± 0.6^{a}	1.11 ± 0.6	2.93 ± 0.6

[a]Significant difference between all groups ($P < 0.01$)

Table 2. Mean ($\pm SD$) values for measures of relative leg stiffness, peak ground reaction force (PGRF) and peak centre of mass displacement (PCoM) pre- and post-fatigue protocol, per age group

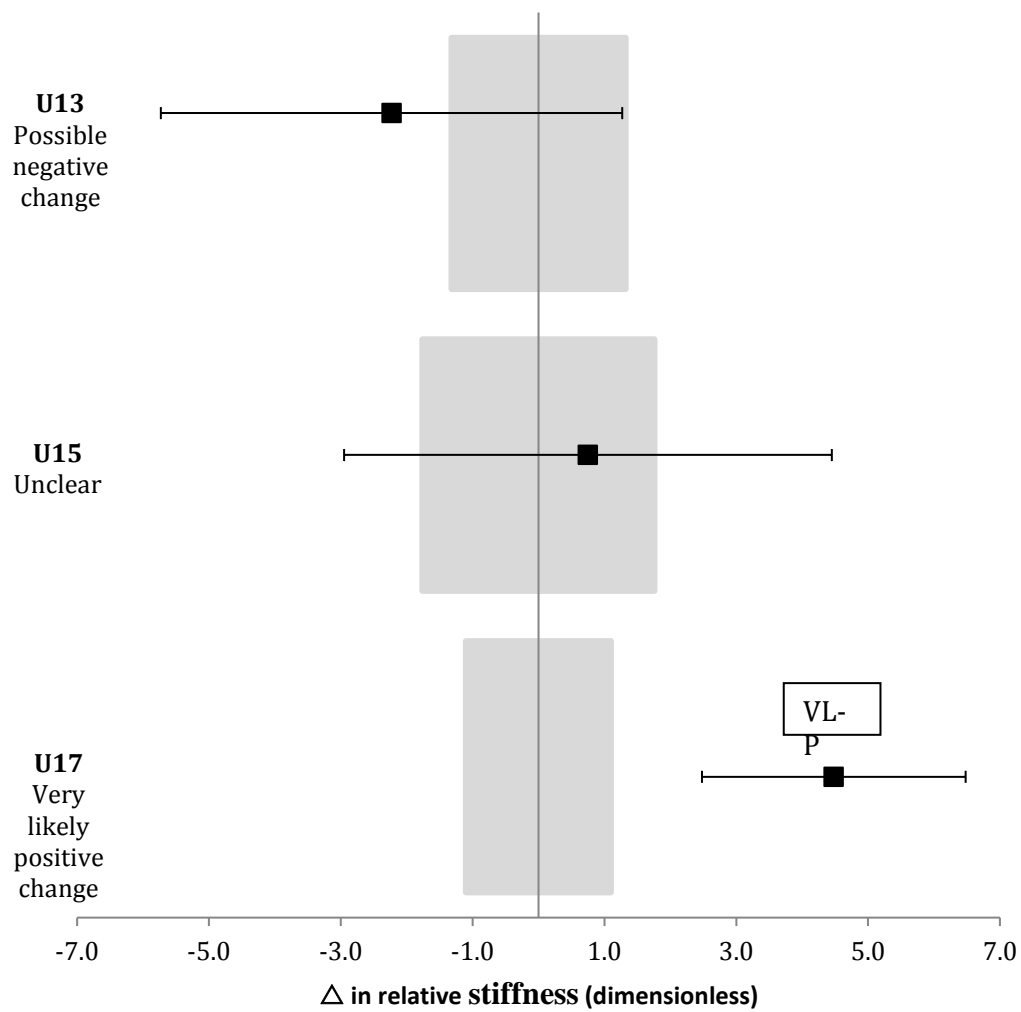| Group / Variable	Pre	Post	Mean difference	$\Delta\%$
Under 13				
Stiffness	44.64 ± 5.5	42.41 ± 7.7	-2.23 ± 7.4	-4.9
Under 15				
Stiffness	46.39 ± 8.8	47.14 ± 6.2	0.75 ± 6.1	$+1.5$
Under 17				
Stiffness	36.46 ± 6.6	40.94 ± 6.1	4.48 ± 4.3	$+12.3$

Figure 1. Mean individual change (90%CI) in U13s, U15s and U17s. The grey shaded area represents trivial change (smallest worthwhile effect). Inferences; Po = possibly, L = likely, VL = very likely, ML = most likely, together with N = negative, P = Positive, where no annotation is provided the inference is unclear