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Vertical stiffness is not related to anterior cruciate ligament elongation in professional rugby union players

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ABSTRACT

Background: Novel research surrounding anterior cruciate ligament (ACL) injury is necessary because ACL injury rates have remained unchanged for several decades. An area of ACL risk mitigation which has not been well researched relates to vertical stiffness. The relationship between increased vertical stiffness and increased ground reaction force suggests that vertical stiffness may be related to ACL injury risk. However, given that increased dynamic knee joint stability has been shown to be associated with vertical stiffness, it is possible that modification of vertical stiffness could help to protect against injury. We aimed to determine whether vertical stiffness is related to measures known to load, or which represent loading of, the ACL.

Methods: This was a cross-sectional observational study of 11 professional Australian rugby players. Knee kinematics and ACL elongation were measured from a 4-dimensional model of a hopping task which simulated the change of direction manoeuvre typically observed when non-contact ACL injury occurs. The model was generated from a CT scan of the participant's knee registered frame by frame to fluoroscopy images of the hopping task. Vertical stiffness was calculated from force plate data.

Results: There was no association found between vertical stiffness and anterior tibial translation (ATT) or ACL elongation (r=−0.05; p=0.89, and r=−0.07; p=0.83, respectively). ATT was related to ACL elongation (r=0.93; p=0.0001).

Conclusions: Vertical stiffness was not associated with ACL loading in this cohort of elite rugby players but a novel method for measuring ACL elongation in vivo was found to have good construct validity.

What are the new findings?

- Anterior tibial translation and anterior cruciate ligament elongation are strongly related.
- Vertical stiffness was not related to anterior tibial translation and anterior cruciate ligament elongation in muscular male elite rugby players.
- That vertical stiffness was not related to anterior tibial translation or anterior cruciate ligament elongation might be because vertical stiffness is associated with increased dynamic knee joint stability.

How might it impact on clinical practice in the near future?

- Vertical stiffness may be trained without fear of increased anterior cruciate ligament injury risk.
- Anterior cruciate ligament elongation may be modelled from anterior tibial translation using the equation y=0.64x+0.24; where y=anterior cruciate ligament elongation and x=anterior tibial translation.

INTRODUCTION

Anterior cruciate ligament (ACL) injury is a severe and common injury to the knee. In the USA, ~80 000 ACL injuries are reported per annum, which equates to 28 injuries per 100 000 people.[1] In Europe, the incidence of non-contact ACL injuries has been reported to be between 34 and 80 injuries per 100 000 people.[2] In addition, research from US collegiate sports and European professional football suggests that incidence of ACL injury has remained relatively unchanged over the past 30–40 years[3 4] in spite of considerable research being undertaken in the area.[4] These statistics are troubling given injury to the ACL leads to impairment of physical function acutely,[3] and many people who sustain an ACL injury develop osteoarthritis in the knee later in life[5–10] and other comorbidities[11 12] making it a chronic issue also.

Unchanged ACL injury rates demand novel prevention strategies that concentrate on dynamic knee joint stability.[4] A mechanism of ACL injury risk mitigation which has not been well studied is vertical stiffness. 'Stiffness' is a mechanical variable derived from Hooke's law in physics which can be applied to human movement. Hooke's law states that the force required to deform an object is related to a proportionality constant (spring) and the distance that object is deformed.[13 14] The 'spring' in this case reflects the viscoelastic properties of the various body tissues and the degree of stiffness is the result of the coordination and interaction of these tissues including tendons, ligaments, muscles, cartilage and bone, and their ability to resist change once force is applied.[15–17] More specifically, vertical stiffness is a measure of whole body stiffness and is defined as the quotient of maximum ground reaction force and centre of mass displacement.[16 18] Therefore, vertical stiffness is subject to the coordination and interaction of tendon, ligament, muscle, cartilage and bone, and the interaction and coordination of dynamic joint stability/stiffness at the spine, hip, knee and ankle joints[16 19–25] (figure 1).

Vertical stiffness has been well researched in the area of sports performance because it has been linked to superior athletic ability,[26–30] and because research has shown stiffness to be easily enhanced. Training programmes which focus on knowledge of performance, movement across uneven or unstable surfaces, strength training and/or plyometrics have all been shown to be effective at increasing stiffness.[13 26 31–35] However, the study of vertical stiffness in the context of sudden or traumatic musculoskeletal injury is relatively novel. Nevertheless, it has been postulated that vertical stiffness is a risk factor for common sporting injuries due to increased vertical ground reaction force.[13 36 37] Some research has argued a relationship between lower limb or vertical stiffness and bony injuries such as stress fracture.[38] However, stress fracture is an overuse injury which can be prevented by effective load monitoring.[39] Thus, stiffness may not be as problematic for overuse injuries, rather accelerated or exponential increases in training load and not adhering to progressive overload training principles might be. Vertical stiffness has also been implicated as a risk factor for hamstring strains in two separate research papers,[40 41] but work by our research group which addressed notable flaws in those studies showed increased stiffness is unlikely a risk factor for muscle strain injury.[42] To the authors' knowledge, no evidence exists to suggest increased vertical stiffness is a risk factor for non-contact connective tissue injury such as ACL strains.

Given that vertical stiffness is partly regulated by joint stiffness, or dynamic joint stability, modifying vertical stiffness may assist in preventing ACL injury particularly non-contact ACL injury. This concept is supported by other work previously undertaken by our research group which showed that greater vertical stiffness is related to increased hamstring and quadriceps preactivation and co-activation,[15] and that increased co-activation of the hamstrings and quadriceps reduces ACL elongation and anterior tibial translation (ATT).[43] Therefore, when vertical stiffness is high knee joint stiffness/dynamic knee joint stability must also be high.[16 25]

It is possible that vertical stiffness as a risk factor for ACL injury has not yet been investigated because measuring ACL stress in vivo has been very difficult and is either invasive or derived from indirect or inaccurate measures. In fact it is only that recent advances in image registration technology, whereby CT images are registered with fluoroscopy (video X-ray) to allow four-dimensional (4D) motion analysis of bone that non-invasive measures become more accurate. This technology, developed by our group, provides the opportunity for measuring kinematics with previously unachievable precision and, for the first time, enables in vivo measurement of ATT.[44–46] Excessive ATT has been implicated in serious knee injuries such as ACL injury.[4] Furthermore, by using a biomechanical model with the image registration technology to locate the ACL attachments, measurement of the distance between those attachments can provide some insight into change in ACL length, or ACL elongation. This is important because the ACL will fail when elongation, or consequent strain, is too great.[43 47]

The aim of this study was to determine if vertical stiffness during a multidirectional hopping task was related to measures which represent loading of the ACL, specifically ACL elongation and ATT. ACL elongation and ATT were measured in vivo using image registration technology with known high precision.[45 46] A secondary aim was to evaluate the relationship between ACL elongation and ATT.

MATERIALS AND METHODS

Experimental approach

This was a cross-sectional observational study of professional male rugby union players. Ethical approval was

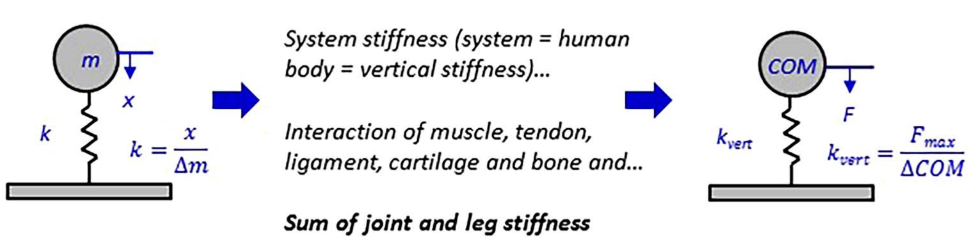

Figure 1 Stiffness (k) is equal to force (x) divided by change in length (Δm). Vertical stiffness (k_{vert}) is a measure of system/whole body stiffness and is equal to maximum vertical ground reaction force (F_{max}) divided by change in whole body centre of mass (ΔCOM). Vertical stiffness therefore is regulated by the function and interaction/coordination of individual anatomical structures and stiffness at joints.

given by the University Human Research Ethics Committee. Written informed consent was obtained from all participants prior to their involvement.

Participants

Participants were conveniently sampled and 11 men were subsequently recruited to this study aged 26.1 ±4.7 years, height 180.5±11.3 cm and mass 85.4±16.5 kg (mean±SD). Each participant was screened by the rugby club's doctor and physiotherapist and deemed to be free of lower limb injury in the 24 months prior to data collection, and all had ACL intact knees.

Procedures

CT data were collected from participants' self-reported dominant leg at 0.5 mm slice intervals on an Aquilion 16 (Toshiba, Tokyo, Japan) 150 mm above and below the knee joint line prior to them performing a bare-foot power-cut hop under fluoroscopy (Axiom Artis MP, Siemens, Munich, Germany). The power-cut hop was a single-leg exercise requiring a 45° jump in the ipsilateral direction onto a designated point on a force platform (Kistler Group, Winterthur, Switzerland), landing on the ipsilateral leg and jumping off as quick as possible at an angle of 90° to land on the same leg at a set distance of 1.0 m (figure 2). A power-cut hop was required as opposed to a running change of direction manoeuvre due to spatial constraints and because this change of direction task best replicated the change of direction manoeuvre typically observed when non-contact ACL injury occurs.[4] CT data were image registered to fluoroscopy and knee joint kinematics and ACL elongation were subsequently measured. Vertical stiffness was calculated from force platform data for each hop and analysed with the image registration output.

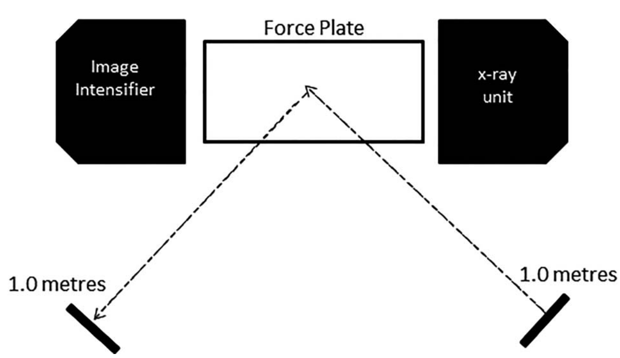

Figure 2 Power-cut hop test. For example, in the above diagram it shows that for a right leg power-cut hop participants would jump off their right leg from the 1.0 m mark on the right of the diagram to land on the centre of the force plate on their right leg, then jump off the force plate as quick as possible before landing on their right leg past the 1.0 m mark on the left of the diagram. The power-cut hop was performed under fluoroscopy to enable construction of a 4D model of the motion of the femur and tibia for knee joint kinematic analysis; hence the centre of the force platform was located in the C-arm of the image intensifier of a fluoroscopy machine. 4D, four-dimensional.

Kinematic analysis

In summary, a 4D model of the motion of femur and tibia was constructed from CT and fluoroscopy data from the power-cut hop test using a technique whereby an algorithm which produces a digitally reconstructed radiograph from CT data and filters it to construct an edge-enhanced image is registered to edge-enhanced fluoroscopy using gradient descent-based image registration. This method has been well described elsewhere.[45 46] Still image examples of image registered output can be seen in figure 3.[43] Knee joint kinematics were subsequently measured in 6-degrees-of-freedom; anterior–posterior movement (eg, flexion and ATT) was measured on the x-axis, superior–inferior movement on the y-axis (eg, compression/distraction) and medial–lateral movement on the z-axis (eg, medial translation, abduction). The long axis of the femur provided the reference for rotation coordinates for the tibia. The error associated with this CT fluoroscopy image registration technique is an SD of 0.38 mm for in-plane translations and 0.42° for rotation.[46]

ACL attachments were mapped to the image-registered output and were defined according to the method used by Grood and Suntay;[48] the proximal attachment at the most superior point of the intercondylar notch of the femur and the distal attachment was assumed the most inferior point between tibial plateau spines. ACL length was considered the distance between those points. Thus, ACL elongation was the change in, or the difference between minimum and maximum, ACL length.

Vertical stiffness measurement

Vertical stiffness was calculated according to the protocol of Cavagna[49] and was therefore considered to be the quotient of maximum vertical ground reaction force and whole body centre of mass displacement. The force platform was interfaced with a personal computer and Bioware software (Kistler Group, Winterthur, Switzerland) was used to record vertical ground reaction force at 1000 Hz for each of the power-cut hops. A 10 Hz high-pass dual-pass Butterworth filter was applied to the raw force plate data. Data were exported from Bioware to purpose built software (BioAlchemy, Adelaide, Australia) for the calculation of vertical stiffness. To calculate the centre of mass displacement the cumulative sum of the vertical ground reaction force (N/s) was integrated, and then point-by-point integration of the previously integrated force was performed. Reliability of this method has been reported elsewhere with typical error of measurement (TEM) of 4.3%. TEM for contact time for the power-cut hopping task was also reported as 1.7%.[15]

Statistical analysis

ATT, change in ACL length and vertical stiffness data are presented as mean±SD. Prior to testing for correlations

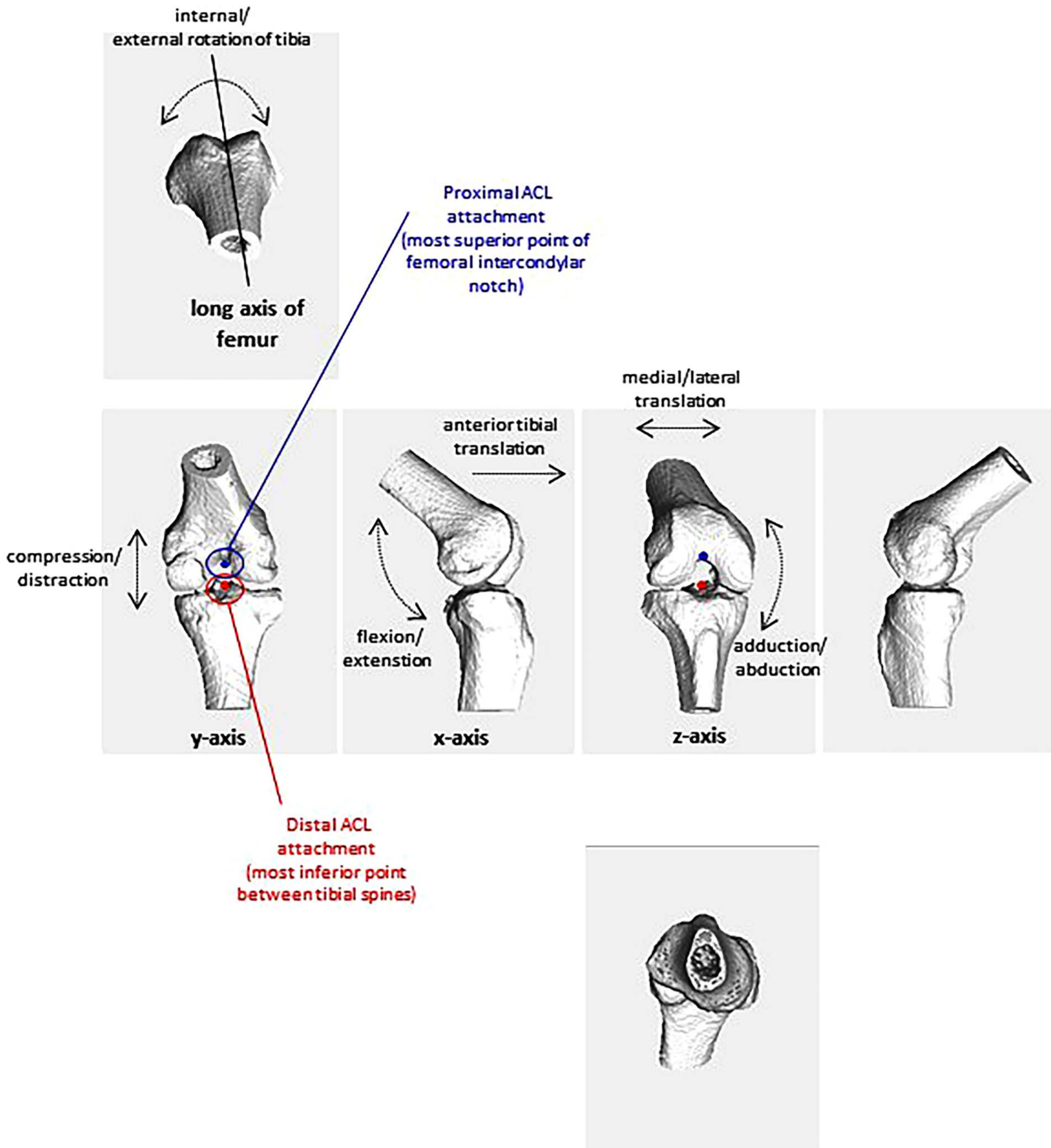

Figure 3 Example of typical CT fluoroscopy image registered output for a step up with descriptions of how the knee joint motion was measured. ACL length was measured as distance the ACL attachments moved relative to each other. ACL, anterior cruciate ligament.

data for ATT, change in ACL length and vertical stiffness were tested for normality with a Shapiro-Wilks test and a Levene's test for homogeneity of variance. Pearson's correlation coefficient was then used to test for the strength of relationship between vertical stiffness and both ATT and change in ACL length. Pearson's correlation coefficient was also used to test the relationship between ATT and change in ACL length. A scatterplot for change in ACL length versus ATT was generated and a linear regression analysis was performed to describe the relationship between ACL elongation and ATT. All statistical analyses were performed using the Statistical Package for Social Sciences (SPSS) software V.19 (IBM).

RESULTS

Vertical stiffness (kN/m) for the power-cut hopping task was 68.31±39.47. Knee kinematics derived from the model showed that ATT was 0.78±0.42 mm and the change in ACL length was 0.84±0.61 mm.

Neither ATT nor ACL elongation appeared to be related to vertical stiffness as demonstrated by a non-

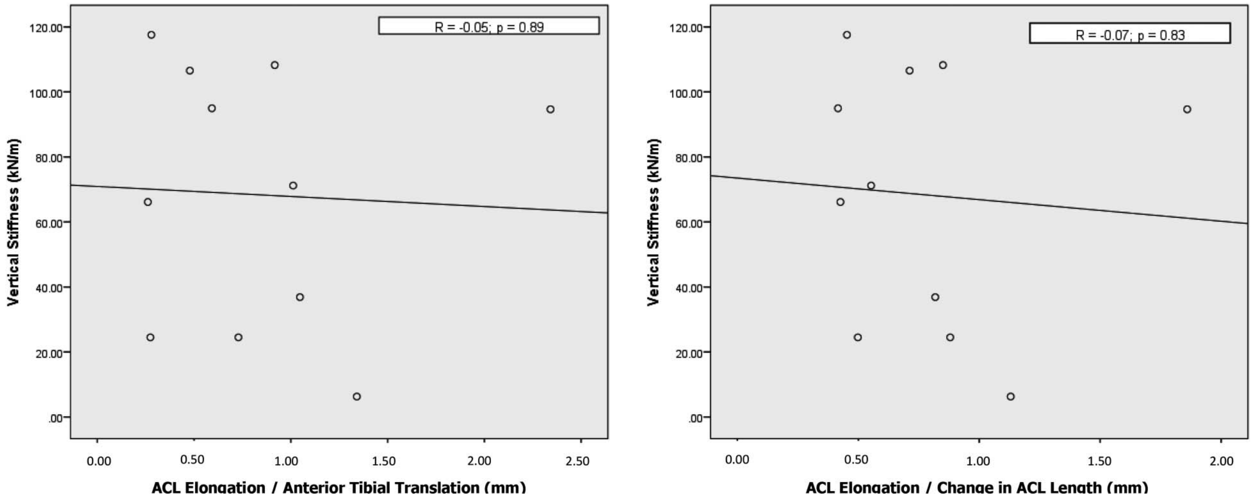

Figure 4 Relationships of vertical stiffness with anterior tibial translation and change in ACL length illustrating no relationship existed. ACL, anterior cruciate ligament.

significant and non-substantial inverse relationship between vertical stiffness and ATT (r=−0.05; p=0.89), and between vertical stiffness and change in ACL length (r=−0.07; p=0.83; figure 4).

ATT and ACL elongation were strongly related as demonstrated by a strong and significant relationship between ATT and change in ACL length (r=0.93; p=0.0001; figure 5). Furthermore, the linear regression analysis revealed that the relationship between ACL elongation and ATT is represented by the equation:

$$y = 0.64x + 0.24$$

where y is the ACL elongation/change in ACL length, and x is the ATT (figure 5) which explained 87% variation in the data.

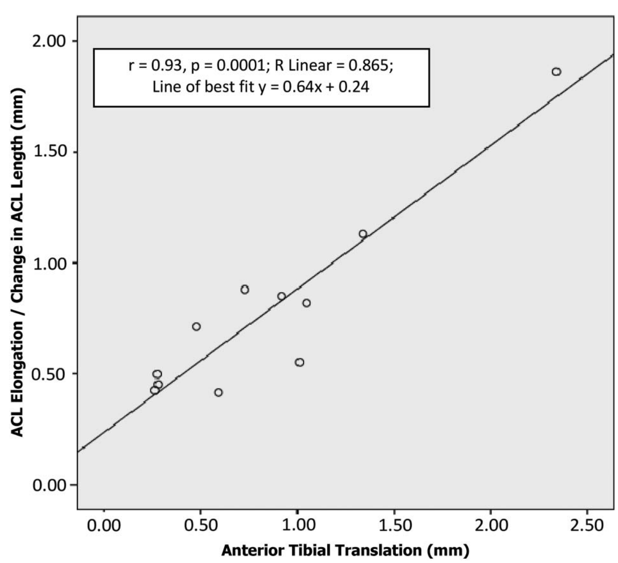

Figure 5 The relationship between ACL elongation (change in ACL length) and ATT. ACL elongation=(0.64×ATT)+0.24. ACL, anterior cruciate ligament; ATT, anterior tibial translation.

DISCUSSION

The main finding of this study was that vertical stiffness was not related to measures which represent ACL loading; specifically ACL elongation and ATT. Furthermore, the novel in vivo method used in this study to measure ACL elongation was shown to have good construct validity as evidenced by a strong relationship between change in ACL length and ATT.

The aim of this study was to examine the theory that, because increased vertical stiffness is related to increased vertical ground reaction force, it is also related to ACL loading.[13 36 37] Participants were tested using a multidirectional hopping task which simulated the change of direction manoeuvre typically seen when non-contact ACL injuries occur. Vertical stiffness was calculated from force plate measurements and ATT and ACL elongation were measured in vivo using a novel image registration method which has been previously validated for measurement of knee kinematics.[45 46 48 49] No relationship between vertical stiffness and ATT or ACL elongation was observed. Therefore, our results do not support others' hypothesis that increased vertical stiffness may be related to increased ACL injury risk because of increased vertical ground reaction force. There are two possible explanations for this result; first and most obviously, vertical stiffness does not contribute to ACL injury risk. Second, our methods were insufficient to detect an association which was actually present.

This study is novel from the perspective that it is the first to measure ATT, ACL elongation and vertical stiffness in vivo while executing a task which simulates the change of direction manoeuvre observed when ACL injury typically occurs. To the best of the knowledge of the authors of the present study, a previous study which has discussed a link between vertical stiffness and ACL injury has only postulated this relationship theoretically.[13 25 36 50 51] In a previous electromyography study, we suggested that vertical stiffness on similar hopping tasks was likely to be related to increased preactivation of the hamstring and quadriceps muscles, particularly when they are co-activated.[15] Furthermore, in another study by our group, and studies by others, have shown that increased co-activation of the hamstring and quadriceps muscles reduced ATT[43 52 53] suggesting that dynamic factors were responsible for increased dynamic knee joint stability. Therefore, while increased vertical ground reaction force might occur with increased vertical stiffness, results from this study, and those of others, suggest that the ACL may not be subject to additional loading secondary to high levels of vertical stiffness because of the primary role played by dynamic knee joint stability. It should be acknowledged, however, that under conditions where extreme anterior–posterior, medial–lateral and/or rotational perturbations are present the magnitude of the vertical ground reaction force may not need to be as great for failure of the ACL to occur. This reasoning is consistent with a previous animal study which showed that ACL stretch and failure was exacerbated by extreme perturbations.[47]

Another possible reason for not finding an association between vertical stiffness and ACL elongation is that our methodology was not sufficiently optimised. The ACL attachment sites used to model ACL elongation was based on those described by Grood and Suntay.[48] According to this method, the proximal ACL attachment is to the most superior point of the intercondylar notch of the femur and the distal attachment is to the most inferior point between tibial plateau spines.[48] However, recent anatomic studies have shown that the proximal attachment is on the medial wall of the lateral femoral condyle[54] and the distal attachment attaches slightly anteriorly to the peak of the medial spine on the tibial plateau.[55] These potential anatomical discrepancies may have affected measurement accuracy[56] and led to our failure to find a relationship between vertical stiffness and ACL elongation. Nevertheless, in this study, ATT was strongly related to ACL elongation indicating good construct validity for this novel method of measuring ACL length.

There were several limitations to this study. First, we did not measure muscle activity concurrently. It would be beneficial to establish further the relationship between thigh muscle activation and any synergistic relationship that may exist between the different quadriceps and hamstring muscles and how they affect ACL elongation on a task similar to that used in the present study. Combined with kinematic data, this may also enable modelling of moments which may provide further insight into the relative force production, and synergistic force production, between muscles surrounding the knee joint. However, with the image registration technology used in this, it is not possible to establish muscle activity relative to ACL elongation. Muscle activity on this task and similar other tasks has been established elsewhere[15] and this must be considered currently. Second, although ATT and ACL elongation were strongly associated they are different measures and therefore can only be surrogates for each other. This is hardly surprising, given that ATT occurs in one plane whereas the ACL length, although primarily modified by anteroposterior stress, is also influenced by mediolateral, rotational and decompressive stresses. Therefore, the relationship found in this study lends support to this novel method of measuring ACL elongation.

CONCLUSION

This study aimed to determine whether increased vertical stiffness is related to ACL loading. We used a novel in vivo method to measure ACL elongation in elite rugby players on a task which stressed the ACL similarly to that which would be observed when ACL injury occurs. This novel method was found to have good construct validity, and our results showed that ACL elongation was not related to vertical stiffness in this cohort of elite rugby players. This study argued that while peak vertical ground reaction force is likely to increase with increased vertical stiffness, it is unlikely to overload the ACL because it is relatively protected due to increased dynamic knee joint stability which is related to increased vertical stiffness. It is possible that the direction of force is more problematic to the ACL. Future studies should also aim to incorporate electromyography and to test more challenging activities where force direction is less predictable.

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Contributors MRP, JMS and PNS were instrumental in developing the image registration technology used in this project. JMS, NBB, DP, JW and BGS all spent considerable time collecting data while MRP contributed significantly to the processing of data. Finally, all authors read and approved the final manuscript.

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Competing interests None declared.

Ethics approval Approved by the ACT Health Human Research Ethics Committee (Protocol ETH.4.11.072), and the Australian National University Human Research Ethics Committee (Protocol 2011/396).

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