SOFT TISSUE LOADS AT THE HUMAN KNEE DURING RUNNING AND CUTTING MANOEUVRES

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Tensile forces on the ACL increase when the knee is in an extended posture and required to accommodate applied moments in flexion, varus, valgus and/or internal rotation. However, the loading of knee joint support structures during sporting actions that are related to non-contact injuries are largely unknown. We studied external loading of the knee during running, side-stepping and cross-over cutting in 10 male subjects under both pre-planned and unanticipated conditions. Soft tissue structures of the knee were exposed to high FE, VV and IE applied moments during the cutting tasks, especially when performed in the unanticipated condition. Whilst muscle activation could accommodate some of this applied load, soft tissue structures were particularly vulnerable during the cross-over cut task where the residual loads were high.

KEY WORDS: knee joint, loading, cutting, injury

INTRODUCTION: More than 5000 football-related anterior cruciate ligament (ACL) injuries occur annually in Australia. Around 60% of these injuries are non-contact and result from the player landing, stopping, running, cutting and sidestepping. The tensile forces on the ACL can dramatically increase when knee is in a more extended posture (< 30° flexion) and accommodating applied moments in combined flexion, varus, valgus and/or internal rotation (Markolf et al., 1995). However, the loading of knee during the aforementioned sporting manoeuvres is largely unknown.

Many of these manoeuvres have to be performed “at the spur of the moment”, leaving the person little time to prepare for the performance of the task. It could be that these unanticipated manoeuvres might place the knee at greater risk of injury than if they are pre-planned.

To better understand the mechanisms for non-contact knee ligament injury, we need to determine the load sharing properties of muscle and other soft tissues during dynamic tasks that challenge the stability of the joint. Forces produced by muscles during these tasks have the potential to counter the external loads applied to the joint, thereby reducing the potential loading of other knee joint soft tissues. The final part of this paper describes the estimation of varus/valgus (VV) moments supported by muscle *in vivo*, and the subsequent potential loading of other knee joint soft tissue structures during running and cutting tasks.

Therefore, the purposes of this paper are three-fold:

- to examine the external knee loading during side-stepping and cross-over cutting;
- to examine the external knee loads when side-stepping and cross-over cutting during unanticipated (UN) and pre-planned (PP) conditions; and
- to estimate the proportion of these loads accommodated by muscle activity during these tasks that challenge the stability of the knee joint.

METHODS: We studied the loading of the knee during normal running (RUN), 30º sidestep (S30), 60º sidestep (S60) and 30º cross-over (XOV) in 10 subjects, running at a speed of 2.7±0.04 m/s, and stepping off their preferred foot. Subjects knew which task was to be performed before they started the approach run under the PP condition. A set of LEDs, positioned within the subjects’ fields of view, controlled the activity. In the PP condition the appropriate LEDs were illuminated early to inform the subject of the required manoeuvre before they started the approach run. However, in the UN condition, the LEDs were illuminated at the latest possible moment, so that the subject was just able to perform the manoeuvre. All cases were presented in random order.

Three dimensional (3D) motions were recorded using a 6-camera Vicon system employing a lower limb marker set (VCM), whilst ground reaction force (GRF) histories were collected synchronously using an AMTI force-platform. EMG recordings using surface electrodes for 10 lower limb muscles were also made. Inter-segmental 3D knee joint moments were estimated using an inverse dynamic model of the lower limbs. The magnitude of resultant GRF was used to determine three phases during stance:

- weight acceptance (WA) (from heel strike to the first trough in the GRF history);
- peak push off (PPO) (time of peak push off force ± 10% of stance time); and
- final push off (FPO) (last 15% of stance).

The externally applied flexion-extension (FE), varus-valgus (VV), and internal-external rotation (IE) joint moments and the knee flexion angle were analysed during these phases. Running speed and cutting angle attained (direction following the manoeuvre with respect to the initial line of travel) were also determined from the trajectory of the pelvic centre. A repeated measures ANOVA was used to determine significant differences with a $p<0.05$.
An electromyography (EMG)-driven Hill-type muscle model that can accurately predict joint moments during running and sidestepping (r^2 = 0.91) was developed. This model takes muscle tendon length and EMG as input to determine *in vivo* forces for 13 muscles crossing the knee. Muscle tendon lengths and moment arms were determined using a 3D anatomical model, developed using Software for Interactive Musculoskeletal Modelling (SIMM©). To measure soft tissue loads, we compared predicted muscle moments in varus/valgus with those measured by inverse dynamics. If the external load applied to the knee was greater than the predicted muscle moments, then this residual had the potential to load the remaining soft tissue structures of the knee.

RESULTS AND DISCUSSION: During the performance of PP trials, knee moments during the PPO phase were generally larger than those recorded in the other phases ($p<0.05$) (Figure 1). There were only very small or no differences between FE moments from the various manoeuvrers. Moving from S60 to XOV, externally applied moments changed from valgus to varus ($p<0.05$) (Figure 1A) and from internal to external rotation (Figure 1B).

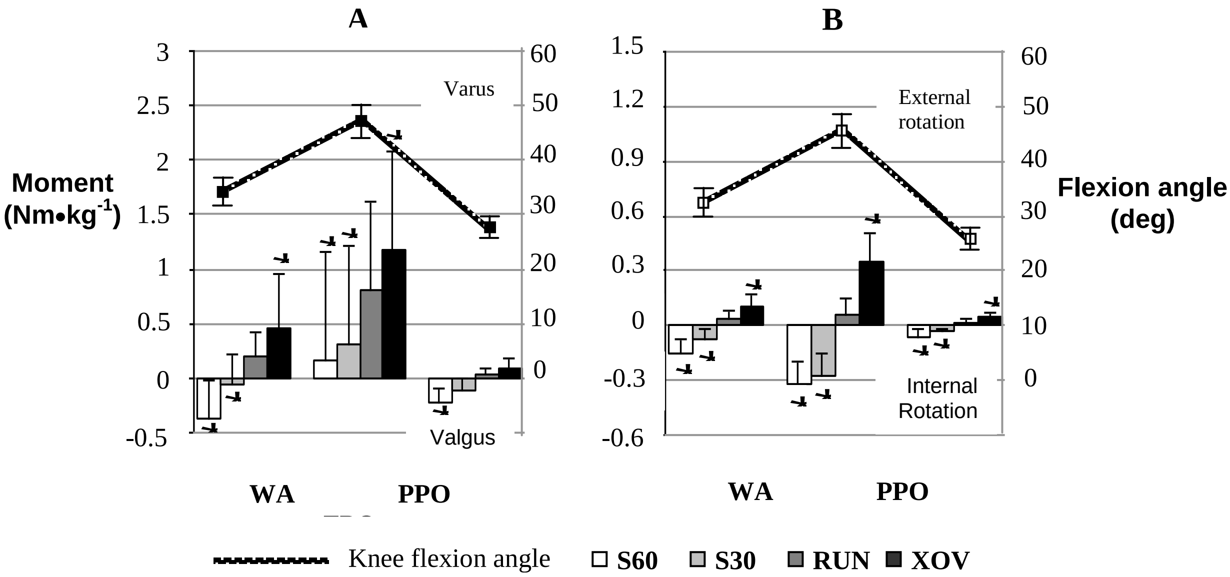

Figure 1 - Moments at the knee: A) varus-valgus, B) internal-external rotation. (*Significantly different to RUN at p<0.05)

During side-stepping there were substantial valgus moments in the WA and FPO phases ($p<0.05$), as well as notable internal rotation moments during WA and PPO ($p<0.05$). The varus moment of the knee during the XOV task was over 2 times larger than that recorded for running ($p<0.05$) during the WA and PPO phases.
The more extended knee angles during WA place the ACL at higher risk of injury, especially during side stepping (S30 and S60) with increased valgus and internal rotation moments. A large varus moment at WA, combined with the applied flexion moment, could increase the risk of ACL injury in the XOV, however, the effect may be moderated due to a concurrent external rotation moment. Even though there is a very large varus moment during PPO the concurrently large applied flexion moment may, in part, reduce the risk of injury to the lateral collateral ligaments. There was no increase in the applied knee flexion moment during side-stepping and cross-over manoeuvres, but the increases in the varus-valgus and internal rotation moments may place the ligaments, especially the ACL, at greater risk of injury.
Unanticipated manoeuvres. In the UN tasks the subject ran marginally slower than for the PP tasks (2.62m/s vs 2.84m/s; $p<0.05$). The cutting angles attained during PP tasks were the same as for the UN tasks, with the exception of the S60 manoeuvre, where UN was smaller than PP (47.9º vs 51.4º; $p<0.05$). There was a general increase in the magnitude of all moments, for each of the manoeuvres (all phases) in the UN compared to PP condition, with the most substantial differences being observed during XOV and S30 tasks. For example, when the knee was in an extended posture (31.26 ± 6.9º) during the WA phase, there was at least a 2-fold increase in the VV moments in the UN condition during the XOV and S30 manoeuvres (Figure 2).

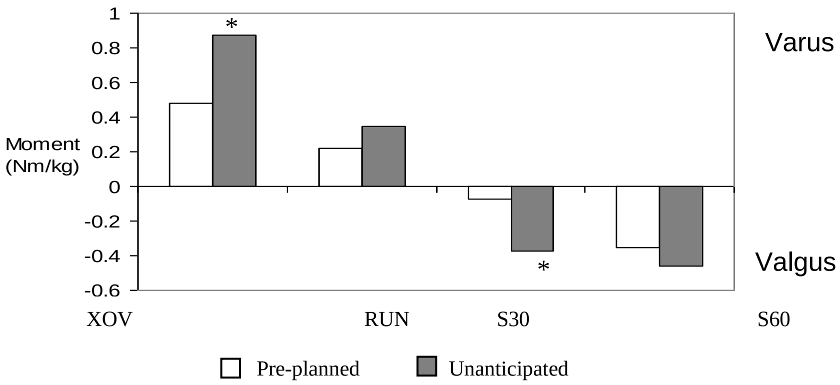

Figure 2 - Varus-valgus moments in the weight acceptance phase. (* UN different to PP; p<0.05)

In the UN tasks the subjects experienced greater applied moments on the knee. Notable increases were observed in applied varus or valgus moments (during XOV and S30 respectively), and internal rotation (during S30). These applied moments have the potential to place large loads on the knee support structures, especially the ACL during side-stepping actions. Such differences were not generally observed in the S60 manoeuvres, because the subjects could not make the required cutting angle and performed the manoeuvre at a slower velocity during the UN condition. Since the magnitude of the cutting angle increased the load on the knee, were subjects able to perform this task under the same conditions as in the PP trials, then the applied knee moments would have been expected to rise accordingly. Summarising, in a game situation during "spur of the moment" changes in direction, athletes would appear to be at greater risk of knee ligament injury when attempting to perform dodging or evading moves compared to those that are pre-planned.
Soft tissue loads. Any externally applied VV load that is not countered by muscle has the potential to load the soft tissue structures of the knee, however it is important to note that the effects of joint reaction force have not been included in these calculations. The current model

did not account for individual ligament, meniscus, or joint capsular forces, so the term 'soft tissue' encompassed all non-muscular components that may contribute to the net VV moment about the knee. The potential VV load placed on soft tissues *in vivo* was therefore determined from the frontal plane joint kinetics.

Potential VV soft tissue load was calculated by subtracting the externally applied VV moment (from inverse dynamics) from the internal VV moment generated by muscle (from the model). If the moment generated by muscle matched that which was applied externally, then no contribution from other soft tissue structures was assumed. However, if the externally applied VV moment was greater than the VV moment generated by muscle, then soft tissue loading may be required to close the joint and a ‘residual load’ was calculated.

For the run and side-step tasks, the varus/valgus moments generated by muscles were greater than the external load applied to the knee, thus no soft tissue loading was required. However, the large varus loads measured during the XOV exceeded the contribution from muscles by up to 1 Nm/kg, thereby potentially loading the soft tissues (Figure 3). A lack of muscular stability when performing the XOV indicated that the ligamentous and meniscal tissues were at greater risk of injury when performing this task.

Furthermore, during a game situation where evading manoeuvres are performed at greater speeds and are often unanticipated, one might expect the applied loads to be greater than those reported in this study. Results from this investigation give us a better understanding of the aetiology of non-contact soft tissue knee injuries, and how muscle activation can assist in the protection of ligaments. Appropriate training methods might be used to alter muscle activation or movement strategies to reduce the load placed on soft tissues and prepare the athlete for these loads during game situations.

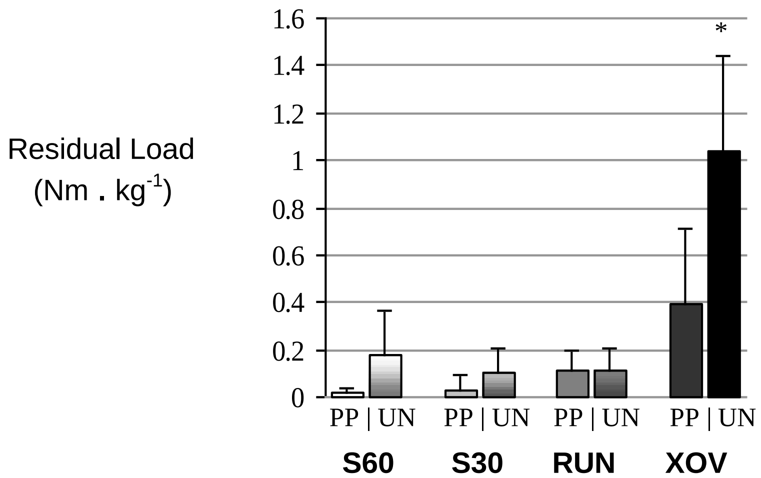

Figure 3 - Peak residual varus/valgus load for PP and UN tasks.

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Acknowledgements

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