Anticipatory effects on knee joint loading during running and cutting maneuvers

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ABSTRACT

BESIER, T. F., D. G. LLOYD, T. R. ACKLAND, and J. L. COCHRANE. Anticipatory effects on knee joint loading during running and cutting maneuvers. *Med. Sci. Sports Exerc.*, Vol. 33, No. 7, 2001, pp. 1176–1181. **Purpose:** To determine how unanticipated performance of cutting maneuvers in sport affects the external loads applied to the knee joint and the potential risk for ligament injury. **Methods:** A 50-Hz VICON motion analysis system was used to determine the lower limb kinematics of 11 healthy male subjects during running and cutting tasks performed under preplanned (PP) and unanticipated (UN) conditions. Subjects performed the UN tasks in response to a light stimulus on a target board. A kinematic model was then used in conjunction with force place data to calculate the three-dimensional loads at the knee joint. **Results:** External flexion/extension moments at the knee joint were similar between PP and UN conditions; however, the varus/valgus and internal/external rotation moments during the UN cutting tasks were up to twice the magnitude of the moments measured during the PP condition. **Conclusion:** Cutting maneuvers performed without adequate planning may increase the risk of noncontact knee ligament injury due to the increased external varus/valgus and internal/external rotation moments applied to the knee. These results are probably due to the small amount of time to make appropriate postural adjustments before performance of the task, such as the position of the foot on the ground relative to the body center of mass. Subsequently, training for the game situation should involve drills that familiarize players with making unanticipated changes of direction. Practice sessions should also incorporate plyometrics and should focus on better interpretation of visual cues to increase the time available to preplan a movement. **Key Words:** UNANTICIPATED, LIGAMENT INJURY, CUTTING, KNEE JOINT LOADS

Our previous investigation measured the external loads applied to the knee joint during running, sidestepping, and crossover cutting tasks in a laboratory setting (3). Subjects were aware of the cutting maneuvers to be performed before starting the approach run and could therefore preplan postural and movement strategies. However, sporting maneuvers are not always anticipated during game situations and usually occur as a sudden reaction to an external stimulus such as avoiding another player or following the bounce of a ball. Hence, it is likely that preplanned cutting maneuvers are not a true reflection of the loads applied to the knee joint during a sporting situation. The previous investigation has provided baseline data (3) with which to compare other conditions that are more likely to represent game situations.

A plethora of motor control literature exists regarding the central nervous system (CNS) response to both anticipated and unanticipated perturbation. These include reflex responses to perturbations during gait (6,7,9,14,22,23,25), muscle activity after perturbations to the upper arm (1,18,26), and the preprogrammed nature of anticipatory postural adjustments (2,4,5,11). Previous research implies that a feed-forward mechanism is used to counter expected perturbations and that anticipated postural adjustments are planned in detail by the CNS (2).

Patla et al. (19) recently showed that movement of the center of mass preceded other kinematic changes to reorient the body when performing a sidestepping task while walking. Two mechanisms were chosen by the CNS to shift the center of mass toward the new direction of travel and included rotation of the trunk about the hips in the frontal plane and repositioning of the foot on the ground, with the latter strategy preferred in the preplanned conditions. However, joint kinetics were not measured by Patla et al.(19), but one might expect to see changes in both direction and magnitude of knee joint loads after a reorientation of the center of mass relative to the foot position on the ground.

Therefore, the purpose of this study was to compare the external loads applied to the knee joint during preplanned and unanticipated running and cutting maneuvers and relate these findings to the potential for noncontact knee ligament injury.

METHODS

Subjects and experimental design. The same subjects from our previous study volunteered for participation in this experiment ($N = 11$). Informed consent was gained before testing to comply with the ethics committee of the University of Western Australia. The tasks chosen for this experiment were the same as that performed in the previous study (3) and included a straight run (RUN), sidestep to 30° (S30) and 60° (S60), and a crossover cut to 30° (XOV). Infrared timing gates were used to monitor the approach running speed (Fig. 1), which was delimited to 3.0 $\text{m}\cdot\text{s}^{-1}$ (~10 $\text{km}\cdot\text{h}^{-1}$). All tasks were performed in a random order,

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0195-9131/01/3307-1176/$3.00/0
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Received for publication October 2000.
Accepted for publication December 2000.

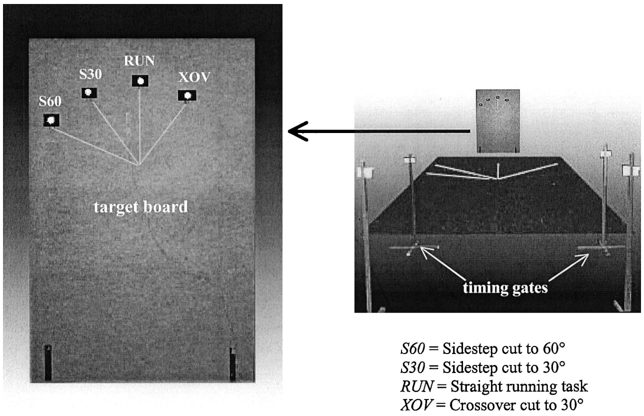

FIGURE 1—Target board and gait laboratory set up. The lights on the target board correspond to the desired direction of travel. Note that these lines of travel are also marked on the floor with tape. The force plate lies at the apex of these lines.

with 10 trials of each maneuver recorded, giving a total of 40 trials per session. However, in this current study, the trials were divided into preplanned (PP) and unanticipated (UN) conditions, as explained below.

A target board was constructed using a set of light emitting diodes (LEDs) to indicate the desired task under both PP and UN conditions (Fig. 1). For all PP conditions, the appropriate LED on the target board was turned on at the beginning of the approach run. For the UN conditions an LED was turned on so that the subject was required to make the decision on which task to perform just before reaching a force plate. The delayed illumination of the LED on the target board was triggered as the subject ran through the timing gates. A “control box” was made to measure and alter the delay between the timing gate trigger and LED illumination. This delay was determined before data collection and altered for each individual to allow for differences in reaction time. At the beginning of the testing session, this delay was reset so the subject did not have enough time to react to the LED and perform the task. The delay was then reduced with each task until that subject had just enough time to correctly perform each maneuver. To obtain appropriate delay times for each individual and reduce potential effects of learning, subjects were required to perform a trial session 1 wk before data collection.

Data collection and analysis. Kinematic, ground reaction force (GRF), and kinetic data were collected using a six-camera, 50-Hz VICON motion analysis system (Oxford Metrics Ltd., Oxford, United Kingdom) and a 1200 × 600 mm force plate at 2000 Hz (Advanced Mechanical Technology Inc., Watertown, MA) as detailed in our previous paper (3).

As described in the previous paper (3) the three-dimensional knee joint moments, knee flexion angles, were determined for the weight acceptance (WA), peak push off (PPO), and final push off (FPO) phases of stance. Approach running speed, task running speed, and cutting angle were also computed for each task (refer to ref. 3 for details of calculations).

Statistical design. All parameters previously defined were analyzed using a three-factor analysis of variance (task × condition × stance-phase) with repeated measures using Datadesk® statistical software (Data Description Inc., Ithaca, NY). Significance was indicated with $P < 0.05$ and Scheffé *post hoc* tests were conducted to determine significant interactions and differences between task and condition.

RESULTS

Speed and cutting angle. The cutting tasks were all performed at slower task running speeds than the RUN task, as indicated in our previous results (Fig. 2). Approach running speed was similar for all trials between UN and PP conditions, as indicated by the speed through the timing gates; therefore, the change in speed occurred throughout the performance of the cutting maneuver. Overall, the UN condition was performed ~0.15 m·s^{-1} slower than the PP condition ($P < 0.05$) (Fig. 2).

The cutting angle measured from the pelvic center during PP and UN conditions of the RUN and XOV tasks indicated that similar angles were achieved regardless of anticipatory condition (Fig. 3). However, the cutting angle during the UN S60 condition was significantly less than the PP condition (53.2° vs 56.2°, respectively, $P < 0.001$). The UN sidestep to 30° was performed at a greater angle than the PP S30 condition (33.1° vs 31.5°, respectively, $P < 0.001$) although, functionally, this difference is probably not important.

Flexion/extension moments. External flexion moments applied to the knee joint at WA and FPO were small compared with those measured at PPO, with little difference between UN and PP conditions (Fig. 4). At PPO, the UN cutting tasks all had significantly different flexion moments compared with the PP condition. There was no significant difference in flexion moments between UN and PP conditions during the RUN task, although the trend was for the UN condition to produce greater flexion loads at the knee ($P = 0.057$). A 6% increase in flexion load was found at PPO when the S30 task was performed UN ($P < 0.05$). In contrast, the UN S60 condition produced 19% less flexion moment at PPO compared with the PP condition ($P < 0.001$), and similarly, in the XOV task there was a 9%

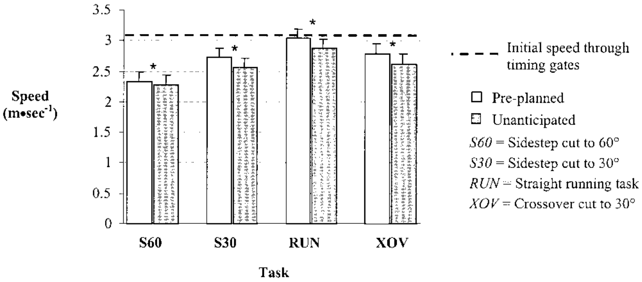

FIGURE 2—Difference in speeds maintained throughout the running and cutting tasks (* significant difference between preplanned and unanticipated conditions; $P < 0.05$). WA, weight acceptance; PPO, peak push off; FPO, final push off.

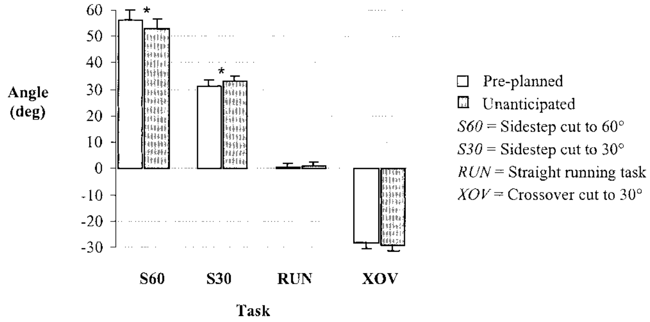

FIGURE 3—Difference in angle attained for the running and cutting tasks (* significant difference between preplanned and unanticipated conditions; $P < 0.01$).

reduction in the external flexion load during the UN condition ($P < 0.001$).

Varus/valgus moments. In general, the VV moments increased when the tasks were performed in the UN condition compared with the PP condition (Fig. 5). External varus loads applied to the knee during the XOV task increased two-fold under UN conditions compared with the PP XOV (Fig. 5). These varus loads were equivalent to 65, 140, and 15 N·m at WA, PPO, and FPO, respectively, for a 75-kg person ($P < 0.001$). Varus moments measured during the UN RUN condition also increased compared with the PP condition; however, the effect was not as large as for the XOV task (Fig. 5) and only significant during PPO with an 18% increase ($P < 0.05$).

The external valgus moments measured at WA during the UN S60 and S30 tasks were 1.5 and 12.3 times the magnitude of the PP conditions, respectively (Fig. 5A), which was equivalent to 39 N·m and 23 N·m for a 75-kg person. Although the magnitude of the valgus moments measured at FPO (Fig. 5C) were less than those measured at WA (Fig. 5A) and PPO (Fig. 5B), there was still a significant increase in these moments when the sidestepping tasks were performed in the UN condition ($P < 0.01$).

The varus/valgus moments measured at PPO for the sidestepping tasks shifted toward valgus during the UN conditions (Fig. 5B). However, as reported in the previous paper (3), there were two distinct groups of subjects who experienced different moments at this stage of the stance phase. Half of the subjects experienced a valgus load (valgus group) during the PP sidestepping tasks, whereas the other half of the subjects experienced a varus moment at PPO (varus group). In the UN condition, the valgus group experienced 55% larger valgus moments compared with the PP condition ($P < 0.01$), whereas the varus group experienced a 34% reduction in the varus load compared with the PP condition ($P < 0.001$); i.e., there was a shift toward valgus. It was interesting to note that no further differences in joint moments were found between these groups at any stages of stance phase or during any other task.

Internal/external rotation moments. As with the VV moments, the IE rotation moments applied to the knee joint during the cutting tasks increased when performed in the UN condition compared with the PP tasks ($P < 0.001$, Fig. 6). Throughout the stance phase, the RUN task did not show any difference in external rotation moments between PP and UN conditions (Fig. 6).

Both sidestepping tasks had greater internal rotation moments at WA in the UN condition compared with the PP condition (49% and 129% increase for S60 and S30, respectively, $P < 0.001$). At PPO, the UN S30 task had a 29% greater internal rotation moment than that measured in the PP condition. Internal rotation moments at FPO during the sidestepping maneuvers were less than that measured at WA and PPO. However, compared with the PP condition, there was a 49% and 66% increase in IE loads in the unanticipated S60 and S30 tasks, respectively ($P < 0.001$).

Across all stages of the stance phase, there was an increase in the external rotation moment applied to the knee during the XOV task when performed in the UN condition compared with the PP condition ($P < 0.001$). External rotation moments during the XOV increased by 90%, 51%, and 38% during the UN condition at WA, PPO, and FPO, respectively (Fig. 6).

Knee flexion angle. There was an overall trend for knee flexion angles to increase when performing the running and cutting tasks under UN conditions (Table 1). Knee flexion increased during the UN condition at WA for the S60, S30, and RUN tasks only ($P < 0.01$).

At PPO, knee flexion increased by 4.0°, 5.4°, 2.7°, and 2.2° for the S60, S30, RUN, and XOV tasks, respectively,

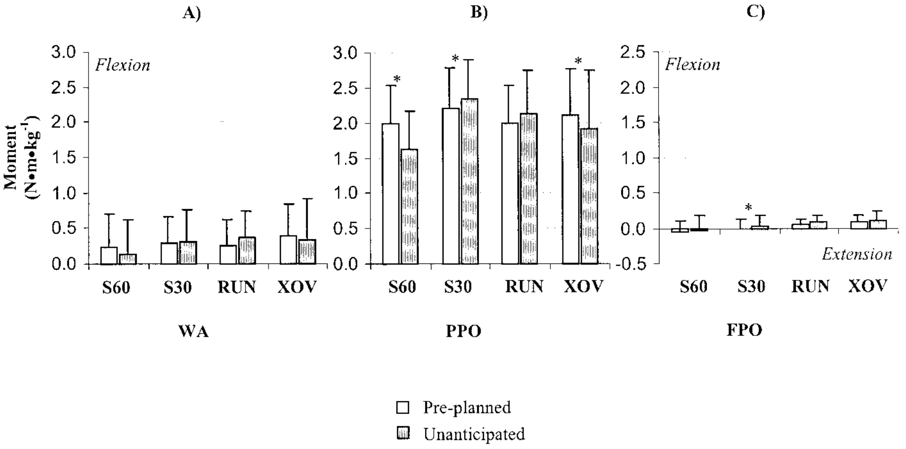

FIGURE 4—Externally applied flexion moments during running, sidestepping and crossover cutting during preplanned and unanticipated conditions (* significant difference between the preplanned and unanticipated conditions; $P < 0.05$).

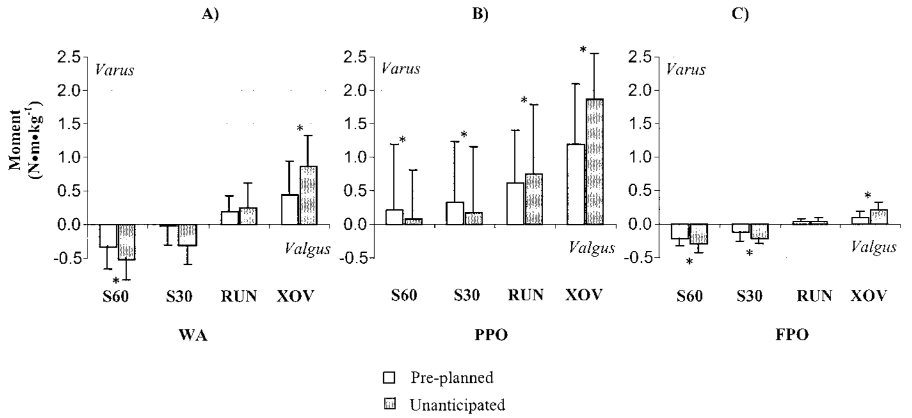

FIGURE 5—Externally applied varus/valgus moments during running, sidestepping, and crossover cutting during preplanned and unanticipated conditions (* difference between preplanned and unanticipated conditions; $P < 0.05$).

under the UN condition compared with the PP tasks ($P < 0.001$). The UN condition at FPO elicited greater knee flexion angles during the S60 and S30 tasks only, with a 2° and 1.5° increase, respectively ($P < 0.05$). The functional significance of these small differences is questionable.

DISCUSSION

The purpose of this study was to compare the external loads applied to the knee joint during preplanned and unanticipated running and cutting maneuvers and relate these findings to the potential for noncontact knee ligament injury. Previous research indicates that anticipating a movement can change reflex responses and postural adjustments to minimize the forthcoming perturbation and maintain an appropriate posture (1,2,14,19,23). The hypothesis that knee joint moments would increase under unanticipated conditions compared with preplanned maneuvers was generally supported, with a large increase in VV and IE moments during the UN cutting conditions. It is believed that the UN condition alters the external moments applied to the knee due to the reduced time to implement appropriate postural adjustment strategies.

Although the exact nature of these postural adjustment strategies were outside the scope of this study, a qualitative analysis of the cutting tasks revealed differences in joint kinematics between UN and PP conditions. These included changes in foot placement on the ground and varying amounts of trunk lean toward the new direction of travel, as found by Patla et al. (19). Further investigation will reveal the exact nature of these postural adjustment strategies and their effect on external loads applied to the knee.

Postural adjustments occur when movements are anticipated and include changes in the position or movement of the center of gravity (2,8,19), altered muscle activation timing or amplitude (2), and changes in reflex muscle activation (1,14,23). In situations where movements are unanticipated there may be little time to make appropriate postural adjustments. In the case of the unanticipated cutting tasks performed in this study, inadequate postural adjustments may have caused the reduction in the performance of the task (reduced cutting angle and speed of execution), and increased external loads applied to the knee (particularly in VV and IE), compared with the preplanned conditions.

Implications for noncontact knee ligament injuries. Our previous study (3) indicated the potential for knee ligament injury during cutting tasks, with combined flexion, VV, and IE loads applied to the knee. It was concluded that external flexion loads combined with large valgus and internal rotation moments are most likely to increase the stress placed on the ACL, particularly at WA when the knee is near full extension (16). The large valgus

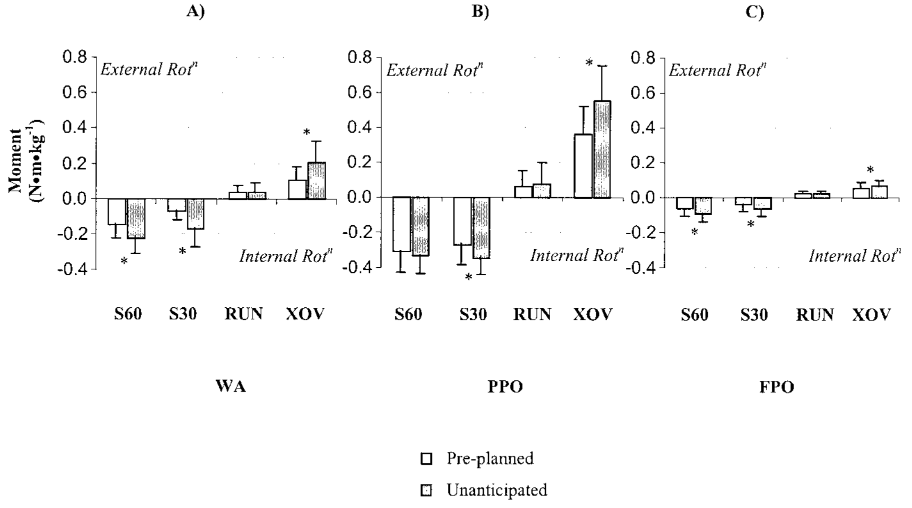

FIGURE 6—Externally applied internal/external rotation moments during running, sidestepping, and crossover cutting during preplanned and unanticipated conditions (* difference between preplanned and unanticipated conditions; $P < 0.05$).

TABLE 1. Average knee flexion angles measured across each stage of the stance for preplanned and unanticipated running and cutting tasks.

Stage of Stance Phase[a]	Task[b]	Condition: Preplanned	Condition: Unanticipated	*P*
WA	S60	32.3°	34.3°	0.005
	S30	31.9°	35.2°	<0.001
	RUN	28.1°	31.5°	<0.001
	XOV	31.4°	31.0°	0.931
PPO	S60	47.4°	51.4°	<0.001
	S30	45.1°	50.6°	<0.001
	RUN	40.4°	43.0°	<0.001
	XOV	43.9°	46.0°	<0.001
FPO	S60	22.7°	24.2°	0.025
	S30	22.5°	24.6°	<0.001
	RUN	21.6°	22.7°	0.197
	XOV	22.3°	23.4°	0.135

[a] WA, weight acceptance; PPO, peak push off; FPO, final push off.

[b] S60, Sidestep cut to 60°; S30, Sidestep cut to 30°; RUN, Straight running task; XOV, Crossover cut to 30°.

moments applied during the sidestepping tasks were most likely to increase the stress placed on the medial collateral ligament (MCL) (3). Similarly, the large external rotation moments applied during the XOV task are likely to increase the stress on the MCL (12). Combined loads of flexion, varus, and external rotation are most likely to place stress on the lateral collateral ligament (16). The VV and IE loads measured during our previous study were within a range of loads that have been shown to cause ligament failure (35–80 N·m of IE rotation or 125–210 N·m of VV rotation; 20).

Given the large increase in VV and IE moments in the UN condition compared with the PP condition, the potential for noncontact knee ligament injury when performing cutting maneuvers in an UN sporting situation becomes apparent. However, muscles crossing the knee joint may be activated to counter these moments, potentially reducing the load placed on knee joint ligaments. Without accounting for knee muscle activation strategies, it is difficult to determine the actual load placed on ligaments. It has been shown that the knee flexors and extensors are both have “bursts” of activity before initial foot contact during a preplanned side-step cut (17). This suggests that muscle activation strategies may be preplanned to stabilize the knee during WA and PPO. We can speculate that the potential for knee ligament injury during UN cutting tasks may increase if muscle activation strategies do not proportionally increase with the large flexion, VV, and IE moments. It is obvious that the activation strategies of muscles crossing the knee during PP and UN cutting maneuvers should be investigated to determine what strategies are adopted by the CNS to counter the external loads applied to the joint.

Although knee flexion increased by a statistically significant amount during the UN condition compared with the PP condition, the functional significance of this increase is difficult to ascertain. The ACL has been shown to be more susceptible to strain at knee postures close to 30° flexion under external flexion and valgus loads (16). Shelburne and Pandy (24) showed that the hamstrings had greater potential to reduce anterior tibial draw when the knee was flexed further from full extension, thereby lowering the ACL load. However, increasing knee flexion from full extension decreases the capacity of the knee muscles to support valgus (and varus) loads (15), thereby potentially raising the loads on the ACL and other ligaments. Therefore, knowledge of the lines-of-action and forces generated by the muscles at particular knee postures is required to understand the functional significance of the increased knee flexion found during the UN condition.

In terms of appropriate interventions to prevent noncontact knee ligament injuries, this study indicates that training should include elements of unexpected and unanticipated movements. The CNS has the ability to selectively alter postural adjustments based on information acquired from previous tasks (27), so training to unanticipated visual cues, such as the tasks performed in this study, may provide an appropriate stimulus for the CNS to refine appropriate postural adjustments. If postural adjustments are made early enough, then the external loads applied to the knee joint could be dramatically reduced. Training program might therefore focus on reducing reaction times to visual and mechanical stimuli. For example, plyometric training has been shown to enhance muscle voluntary reaction times and reduce the time taken for muscles to produce peak torque (10,21). Hamstring voluntary reaction times and time to peak torque have also improved (i.e., reduced) in subjects who have undergone a stability and balance training program (13). In addition, training for the game situation should involve drills that familiarize players with making rapid changes in direction, rather than having cutting tasks being preplanned. The cutting directions could be indicated to the player during an approach run, with the amount of forewarning being incrementally reduced to make the tasks more difficult as the player becomes more proficient. Other interventions could also include retraining muscle activation strategies to counter the loads experienced during sidestepping and crossover cutting maneuvers. This may improve the muscular support of the external loads, thus reducing the potential loading of ligaments. Whether these neuromuscular changes map over into performance of the sporting tasks remains to be seen.

Differences in VV loads at PPO found between subjects during the PP sidestepping tasks indicated that technique might have a substantial effect on the loads applied to the knee joint. Further investigation should determine differences in whole body kinematics between the valgus group and varus group, and between the preplanned and unanticipated performance of the maneuvers. This may help ascertain the movement and postural patterns that reduce knee loading during cutting tasks, which could be used in a technique training intervention.

SUMMARY

The external VV and IE moments applied to the knee joint during UN cutting maneuvers were up to twice the magnitude of those experienced under PP conditions. These large increases in VV and IE moments may substantially increase the loading of knee joint ligaments, particularly if muscles are not activated to counter the increase in external load placed on the joint. It is hypothesized that inappropriate postural adjustments are responsible for the increase in joint load when there is little time to prepare for the task, and further research should focus on the nature of these postural adjustments. Muscle activation patterns during both PP and UN cutting maneuvers should also be investigated to determine whether muscles are activated accordingly to counter the increased external loads placed on the knee and protect knee joint ligaments.

We believe that primary prevention of knee ligament injury is possible, given appropriate intervention strategies. Potential intervention strategies should focus on the following areas: a) reducing the external load applied to the knee joint by changing technique of postural adjustments; b) improving reaction time to allow more time to make appropriate kinematic adjustments during game situations; and c) better interpretation of visual cues to increase the time available to preplan a movement. Training programs should be developed to address these issues, such as training that includes unanticipated sporting movements and plyometrics.

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REFERENCES

1. Bennis, N., A. Roby-Brami, M. Dufosse, and B. Bussel. Anticipatory responses to a self-applied load in normal subjects and hemiparetic patients. *J. Physiol. Paris* 90:27–42, 1996.
2. Benvenuti, F., S. J. Stanhope, S. L. Thomas, V. P. Panzer, and M. Hallett. Flexibility of anticipatory postural adjustments revealed by self-paced and reaction-time arm movements. *Brain Res.* 761: 59–70, 1997.
3. Besier, T. F., D. G. Lloyd, J. L. Cochrane, and T. R. Ackland. External loading of the knee joint during running and cutting manoeuvres. *Med. Sci. Sports Exerc.* 33:1168–1175, 2001.
4. Bouisset, S., and M. Zattara. Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. *J. Biomech.* 20:735–742, 1987.
5. Brown, J. E., and J. S. Frank. Influence of event anticipation on postural actions accompanying voluntary movement. *Exp. Brain Res.* 67:645–650, 1987.
6. Dietz, V., J. Quintern, G. Boos, and W. Berger. Obstruction of the swing phase during gait: phase-dependent bilateral leg muscle coordination. *Brain Res.* 384:166–169, 1986.
7. Eng, J. J., D. A. Winter, and A. E. Patla. Strategies for recovery from a trip in early and late swing during human walking. *Exp. Brain Res.* 102:339–349, 1994.
8. Ferris, D. P., K. Liang, and C. T. Farley. Runners adjust leg stiffness for their first step on a new running surface. *J. Biomech.* 32:787–794, 1999.
9. Garrett, M., and R. G. Luckwill. Role of reflex responses of knee musculature during the swing phase of walking in man. *Eur. J. Appl. Physiol.* 52:36–41, 1983.
10. Hakkinen, K., and P. V. Komi. Training-induced changes in neuromuscular performance under voluntary and reflex conditions. *Eur. J. Appl. Physiol.* 55:147–155, 1986.
11. Horak, F. B., P. Esselman, M. E. Anderson, and M. K. Lynch. The effects of movement velocity, mass displaced, and task certainty on associated postural adjustments made by normal and hemiplegic individuals. *J. Neurol. Neurosurg. Psychiatry* 47:1020–1028, 1984.
12. Hull, M. L., G. S. Berns, H. Varma, and H. A. Patterson. Strain in the medial collateral ligament of the human knee under single and combined loads. *J. Biomech.* 29:199–206, 1996.
13. Ihara, H., and A. Nakayama. Dynamic joint control training for knee ligament injuries. *Am. J. Sports Med.* 14:309–315, 1986.
14. Komiyama, T., and T. Kasai. Changes in the H-reflexes of ankle extensor and flexor muscles at the initiation of a stepping movement in humans. *Brain Res.* 766:227–235, 1997.
15. Lloyd, D. G., and T. S. Buchanan. A model of load sharing between muscles and soft tissues at the human knee during static tasks. *J. Biomech. Eng.* 118:367–376, 1996.
16. Markolf, K. L., D. M. Burchfield, M. M. Shapiro, M. F. Shepard, G. A. Finerman, and J. L. Slauterbeck. Combined knee loading states that generate high anterior cruciate ligament forces. *J. Orthop. Res.* 13:930–935, 1995.
17. Neptune, R. R., I. C. Wright, and A. J. van den Bogert. Muscle coordination and function during cutting movements. *Med. Sci. Sport Exerc.* 31:294–301, 1999.
18. Pantaleo, T., F. Benvenuti, S. Bandinelli, M. A. Mencarelli, and A. Baroni. Effects of expected perturbations on the velocity control of fast arm abduction movements. *Exp. Neurol.* 101:313–326, 1988.
19. Patla, A. E., A. Adkin, and T. Ballard. Online steering: coordination and control of body center of mass, head and body reorientation. *Exp. Brain Res.* 129:629–634, 1999.
20. Piziali, R. L., D. A. Nagel, T. Koogle, and R. Whalen. Knee and tibia strength in snow skiing. In R. J. Johnson, W. Hauser, and M. Magi (Eds.). *In Ski Trauma and Skiing Safety IV.* Munich: TUV Publication Series, 1982, pp. 24–31.
21. Sale, D. G. Neural adaptation to resistance training. *Med. Sci. Sports Exerc.* 20(Suppl. 5):S135–145, 1988
22. Schillings, A. M., B. M. Van Wezel, and J. Duysens. Mechanically induced stumbling during human treadmill walking. *J. Neurosci. Meth.* 67:11–17, 1996.
23. Schillings, A. M., B. M. H. Van Wezel, T. Mulder, and J. Duysens. Widespread short-latency stretch reflexes and their modulation during stumbling over obstacles. *Brain Res.* 816:480–486, 1999.
24. Shelburne, K. B., and M. G. Pandy. A musculoskeletal model of the knee for evaluating ligament forces during isometric contractions. *J. Biomech.* 30:163–176, 1997.
25. Sinkjaer, T., J. B. Andersen, and B. Larsen. Soleus stretch reflex modulation during gait in humans. *J. Neurophysiol.* 76:1112–1120, 1996.
26. Soechting, J. F., and F. Lacquaniti. An assessment of the existence of muscle synergies during load perturbations and intentional movements of the human arm. *Exp. Brain Res.* 74:535–548, 1989.
27. Toussaint, H. M., Y. M. Michies, M. N. Faber, D. A. Commissaris, and J. H. van Dieen. Scaling anticipatory postural adjustments dependent on confidence of load estimation in a bi-manual whole-body lifting task. *Exp. Brain Res.* 120:85–94, 1998.