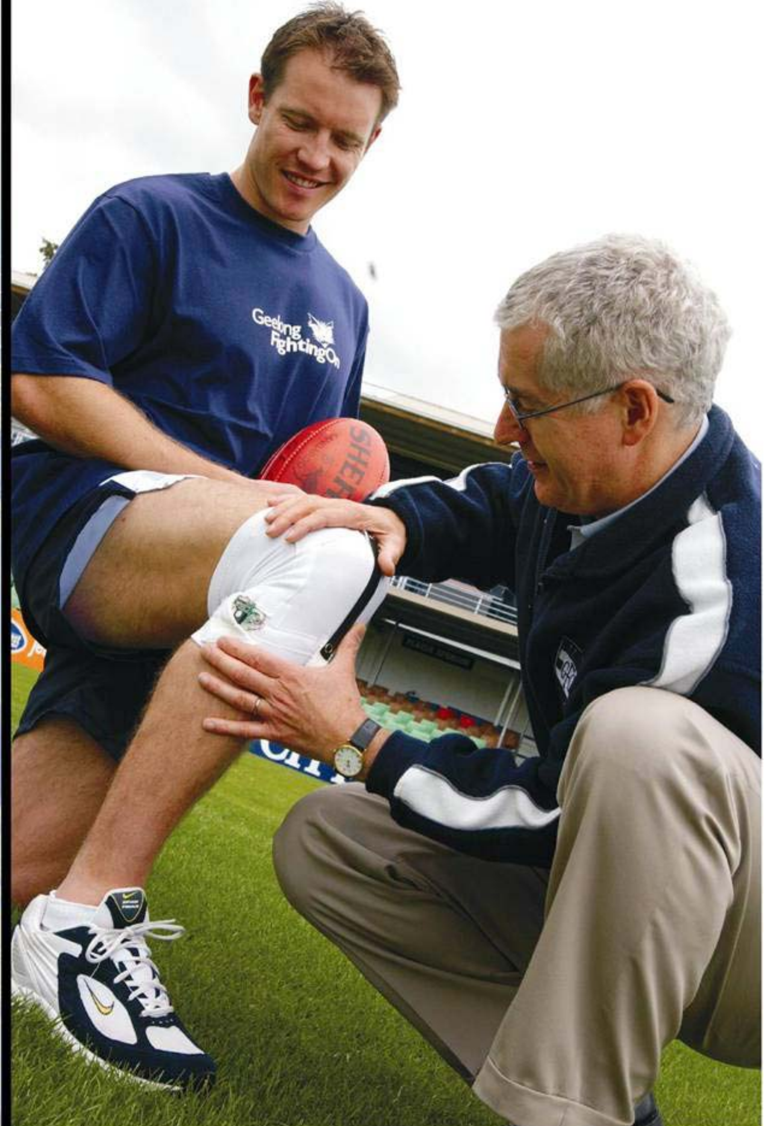
Intelligent Knee Sleeve:

Can it be used to decrease susceptibility to anterior cruciate ligament injury?



Final Report to the NSW Sporting Injuries Committee

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Overview

Non-contact rupture of the anterior cruciate ligament (ACL) is one of the most common disabling injuries an athlete can sustain. ACL rupture frequently results from poor landing technique and accounts for a quarter of all sports injury costs in Australia, with ACL reconstructive surgery often being the only viable treatment option. It is therefore imperative that innovative ACL injury prevention strategies are developed. The merging of materials science, textile engineering and biomechanics has led to the development of the Intelligent Knee Sleeve (IKS), a wearable device capable of providing immediate and individualised feedback to the wearer about their landing technique and, therefore, has been advocated as an innovative tool which could be used in ACL injury prevention programs. This study aimed to determine whether receiving audible feedback from the IKS during participation in a landing training program could change the landing motion of athletes, so that they adopted a safer knee flexion angle during dynamic landing movements.

Thirty athletes (mean 22.9 years, range 19-30) involved in landing sports and with no history of knee joint disease were randomly assigned to one of three groups: (a) an IKS Trained group, (b) a Placebo Trained group or (c) a Control group. Subjects in the IKS Trained and Placebo Trained groups participated in a six week landing training program focusing on correct landing mechanics, completing three 30 minute training sessions per week; the only difference between the two groups being whether feedback was provided by the IKS during training. All subjects underwent laboratory-based biomechanical assessment of their landing technique pre- and post-intervention and 3 months post-intervention. Mean and percentage change data were then analysed using a one-way repeated measures ANOVA with one between factor (subject group) to determine whether subjects significantly ($p \leq 0.05$) changed their landing technique when performing abrupt deceleration tasks after landing training using the IKS.

Landing training was proven successful in terms of teaching skilled athletes to reduce the forces that they generated at landing, irrespective of the feedback received during training. However, providing skilled athletes with immediate feedback about their knee flexion during a six week landing training program using the IKS, tended to assist them to increase their knee flexion angle more so than skilled athletes who participated in a similar landing training program but without any feedback, although between-group differences in knee flexion following the intervention were not statistically significant. That is, the IKS Trained group increased their maximum knee flexion angle from pre- to post-intervention an average of 8°. In contrast, neither the Placebo Trained group nor the Control group increased their maximum knee flexion over the six weeks. In fact, both these two latter groups displayed a reduction in their average maximum knee flexion angles over the six weeks by 2° and 5°, respectively. Furthermore, the athletes responded in a variety of different ways to the training programs, irrespective of feedback, in terms of the manner in which they recruited their lower limb muscles in preparation to land. As subjects in the present study were injury-free throughout the study, it was speculated that this variability represented each subject using muscle activity patterns that may have been optimal for them to control their lower limbs during landing.

It was concluded that following a landing training program using the IKS, athletes did display greater changes in knee flexion when landing from a jump, although these changes were not statistically significant and require further investigation, given the low statistical power. Furthermore, whether changes in knee flexion angle decrease the incidence of ACL injuries in sports that require landing movements warrants further investigation.

Introduction

Knee injury – The effects

The human knee joint has a high susceptibility to injury due to its incongruent structure and the high forces imposed on the joint, particularly during dynamic activities such as landing. Of all the knee ligaments, the ACL is the most frequently injured (Johnson, 1983), with an injury frequency nine times greater than that of the posterior cruciate ligament (Tibone, 1986). When the native ACL is ruptured, the knee joint is predisposed to episodes of giving way, further risk of meniscal damage, loss of proprioception via damage to mechanoreceptors in the joint and ligament itself, recurrent pain, and likely degeneration of the knee joint as a result of excessive laxity and persistent instability (Acierno, 1995). Consequently, ACL reconstructive surgery often becomes the only viable treatment option whereby athletes can return to competitive sport. However, ACL reconstruction may result in losses of joint range of motion, muscle strength and control (Draper, 1990) such that an asymmetric loss of flexion and extension radically affect those involved in running or jumping sports (Millett, 2001). While early recognition and aggressive intervention can usually prevent significant disability or permanent functional impairment (Millett, 2001), ACL rupture is debilitating, particularly for young athletes and may end promising sporting careers.

In Australia, although knee injuries account for only 12% of the total sport injuries, they represent 25% of total injury costs (Egger, 1990). Unfortunately, it is in Australia's most popular participation sports, such as netball, basketball and the football codes, that knee injuries commonly occur (Seward, 1997). Egger (1990) estimated that the direct cost of knee injuries in sport per year was as high as $11.9 million for Rugby League/Union, $8.8 million for Australian Rules football and $5.3 million for non-contact sports such as netball. These costs have continued to escalate over the past decade. The costs of an ACL injury involve those for surgery and rehabilitation, due to the initial injury, and ongoing reoccurrences and lost playing time (Cochrane, 2001). Future degenerative joint problems are also likely making an ACL injury more costly and insidious (Cochrane, 2001; Noyes, 1997; Shelbourne, 1991). Therefore, knee injuries in sport pose a serious problem indicating the urgent need to implement appropriate intervention programs to help reduce the incidence of ACL injury.

Knee injury – Is prevention feasible?

Mechanisms of ACL injury in sport can be classified into two main categories: (a) contact injuries caused when an external force is applied to the knee causing ACL rupture and (b) non-contact injuries caused when an indirect force is applied to the knee (Zarins, 1983). Typically, non-contact ACL injury involves rapid deceleration, quick changes in direction (Bartold, 1997) and/or abrupt landings, often accompanied by poor landing technique (Cochrane, 2001; Hume, 1997; Markolf, 1995). It has been estimated that 66% to 78% of ACL injuries occur via non-contact mechanisms (Arendt, 1995; Baker, 1990; Noyes, 1983). Whereas contact injuries have mainly been attributed to chance, non-contact ACL injuries are more related to characteristics of the injured individual, such as the degree of muscular weakness or muscular coordination, and therefore the movement pattern performed at the time of injury (Bender, 1964; Dvorak, 2000a). Studies report that most non-contact knee injuries occur at knee angles of less than 30° (Boden, 2000; Cochrane, 2001) where quadriceps contraction increases ACL strain (Boden, 2000; Draganich, 1990; Hirokawa, 1992; Renstrom, 1986; Torzilli, 1994; Wilk, 1996) and the hamstrings are less effective in protecting the ACL by resisting the resulting anterior tibial translation (Pandy, 1997). Therefore, as landing tasks require large external knee flexion moments to be generated, and thus high quadriceps activation (Besier, 2001; Colby, 2000), where poor landing technique is displayed, it would appear feasible to prevent non-contact ACL injuries by correcting this poor technique.

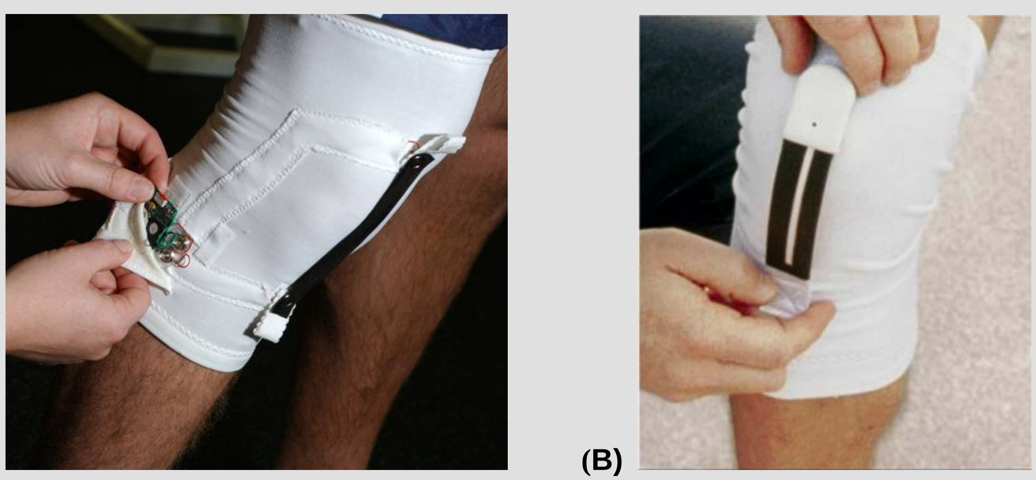
Can landing technique be readily changed to ensure safer landings?

It has been shown that providing verbal feedback to subjects before they perform a vertical drop jump results in the subjects generating lower ground reaction forces upon landing compared to not receiving feedback (Prapavessis, 1997). That is, athletes can quickly and effectively assimilate verbal instructions so as to modify their lower limb movement patterns to generate less force upon ground impact. Based on this reduction in ground reaction forces upon landing it has been suggested that it should be possible to train athletes to modify their landing technique to reduce their risk of injury. The benefits of landing programs in reducing knee injuries have also been acknowledged by the implementation of landing training programs for Australian Football League players (Seward, 1999), and female soccer, volleyball and basketball players (Hewett, 1999; Hewett, 1996).

Extensive work by Steele and her colleagues (1987a; 1987b) has also shown that flexing the knees throughout the landing action can "cushion" the forces over a longer time and thereby reduce the jarring effects of landing. Increased knee flexion also lowers a player's centre of gravity which, in turn, enhances their stability (Steele, 1987a; Steele, 1987b). To reduce knee injury at landing, a relatively high flexion angle should be combined with a large range or amplitude of joint motion over which to dissipate the energy in muscles (Cochrane, 2001; Mizrahi, 1982a; Mizrahi, 1982b). Greater knee flexion will also allow the hamstring muscles to activate more effectively to protect against ACL strain (Cochrane, 2001).

How could the Intelligent Knee Sleeve help?

The Intelligent Knee Sleeve (IKS) is a simple, inexpensive sleeve of lycra-like material, incorporating a fabric strain gauge into part of an electronic circuit (Figure 1) whereby an audible signal is emitted based on changes in *knee flexion angle*. The IKS was successfully trialed in a landing training program integrated into strength and conditioning sessions with Australian Football League players from Geelong Football Club and was proved valid (Intraclass Correlation Coefficients: R_1 = 0.903 to 0.988) and reliable (± 8° at shallow angles and ± 5° at deep angles) in a laboratory-based trial (Munro *et al.*, 2002).



(A) (B)

Figure 1 The original (A) and most recent (B) prototypes of the Intelligent Knee Sleeve.

It has been suggested that the IKS could be used to train players to land correctly, that is, to flex their knees through a desirable range of motion throughout the landing action and, in turn, reduce the risk of injury. Without the immediate feedback provided by the knee sleeve, athletes are currently restricted to "guessing" if they are bending their knees sufficiently when performing landing drills as the movements are performed too quickly to enable coaches to accurately "eyeball" the landing knee angles (Genaidy *et al.*, 1993). The knee sleeve therefore has the advantage of providing immediate individualised feedback to any player wearing the device during a training program, thereby increasing the objectivity, frequency and speed of feedback. However, no study has been conducted to confirm whether this type of immediate feedback with respect to knee joint flexion is effective in training athletes to flex their knees more after performing a dynamic landing task.

Aims & Hypotheses

What did we aim to achieve?

This study aimed to determine whether the IKS, which provides audible feedback with respect to knee flexion angle, could be used by athletes to learn how to land correctly to protect their ACL from injury.

What did we hypothesise?

Based on previous literature, we hypothesised that, following a landing training program using the IKS, athletes would display greater knee flexion when landing from a jump which, in turn, would decrease the forces of landing and place the hamstrings muscles in a better position to protect the ACL.

Methods & Procedures

Subjects

Seventeen male and 20 female athletes with no history of knee joint disease or trauma (confirmed by a score > 80 on the Lysholm Knee Scoring System) volunteered to participate in the present study. Subjects were recruited from sporting teams within the Illawarra, NSW, who were experienced in sports which involve abrupt deceleration movements and catching balls and which have a high incidence of ACL injuries (for example, netball, basketball and most football codes). Subjects, matched for age, height, mass, limb dominance and playing ability, were randomly allocated to one of the following three groups:

1) subjects who, in conjunction with their normal training, participated in a landing training program wearing the IKS, receiving regular audible feedback based on knee flexion angle throughout the training– "IKS Trained";
2) subjects who, in conjunction with their normal training, participated in a landing training program wearing the IKS but did not receive any audible feedback as the knee sleeve components providing sound were <u>not</u> connected) – "Placebo Trained"; and
3) subjects who completed their normal training and without any additional training using the IKS – "Control".

Written informed consent was obtained from all subjects, and all biomechanical testing was conducted according to the NHMRC Statement on Human Experimentation (National Health and Medical Research Council, 1994) after being approved by the University of Wollongong Human Research Ethics Committee.

Although 57 athletes initially indicated a willingness to participate in the study, 20 withdrew their interest once they were randomly allocated to the groups. For example, those very keen to participate in the landing program withdrew if allocated to the Control group because they wanted to complete the training program or, conversely, those willing to be controls withdrew if allocated to a training group due to the intensive time demands of the study. Of the 37 subjects who consented to take part in the study and participated in the initial data collection phase, 7 withdrew during the study due to sports injuries unassociated with the landing training program or the testing sessions (5 subjects), relocation (1 subject) or pregnancy (1 subject). Although this rate of withdrawal was higher than anticipated, 30 subjects (5 males and 5 females per group) were considered adequate to achieve a statistical power of 80% when detecting significant intervention effects of 5° change in knee flexion angle at $p \leq 0.05$. The characteristics of the subjects within each group are detailed in Table 1, with no significant differences found between the groups with respect to any of the descriptive characteristics.

Although completing the pre- and post-training testing sessions, a further 15 subjects withdrew from the study before the 3 month post-intervention testing session, again due to factors beyond the control of the chief investigators: injury unassociated with the study (2 subjects), relocation (10 subject) or withdrawn consent (3 subject). Consequently, statistical procedures were not completed on the 3 month post-intervention data.

Table 1 The descriptive characteristics of subjects in the IKS Trained, Placebo Trained and Control groups.

Variable	IKS Trained	Placebo Trained	Control	*p*-value
Number	10	10	10	----
Age (years)	25.2 ± 4.45	22.0 ± 3.24	23.6 ± 3.80	0.136
Height (m)	1.81 ± 0.12	1.75 ± 0.08	1.76 ± 0.11	0.335
Mass (kg)	79.1 ± 17.4	69.3 ± 7.4	73.6 ± 17.8	0.264
Lysholm score†	94.6 ± 5.3	98.4 ± 3.1	96.6 ± 4.6	0.112

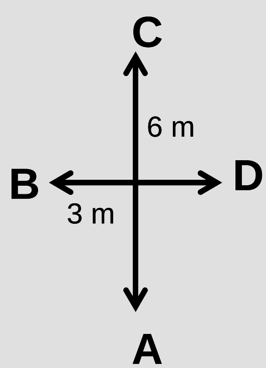
† The Lysholm Knee Scoring Scale rates knee pain and functionality out of a possible 100 points, indicating a fully functional and pain-free knee.

Experimental protocol

After recording height and mass and completing the functional tests, limb dominance was established by asking each subject to hold a football and simulate kicking for goal. The stance or non-kicking lower limb was then defined as the "dominant" or test limb for all further data collection and the functional tests were completed. Subjects were then assessed performing a rapid horizontal deceleration task whereby they were required to accelerate forwards for approximately three paces and then leap from their non-test limb to land on their test limb in single-limb stance, with their foot centrally located on a force platform whilst catching a ball. This landing movement was selected as it has been identified as excessively loading the ACL and represents a typical mechanism of non-contact ACL injury (Cowling *et al.*, 2003; Steele, 1997). The landing actions were performed for 10 trials before and after the six week intervention and after 3 months post-intervention. Subjects were allowed adequate rest between each trial to minimise fatigue. Activity diaries were kept by all subjects and monitored weekly over the six week period. All testing was conducted at the Biomechanics Research Laboratory at the University of Wollongong.

Functional tests

After completing a warm up to minimise injury risk during testing, subjects completed seven functional assessment tasks: a modified lower extremity functional test (mLEFT); a maximal vertical jump (MVJ); a maximal vertical hop on the dominant (MVD) and non-dominant (MVND) lower limbs; a maximal horizontal jump (MHJ); and a maximal horizontal hop on the dominant (MHD) and non-dominant (MHND) lower limbs. For the maximal vertical assessments, subjects stood next to a wall and then were able to use their upper limbs before leaping maximally in the vertical direction to place a chalk mark on the wall. For the maximal horizontal assessments, subjects started with their toes behind a mark and were able to use their upper limbs to assist them to leap horizontally across the floor where the distance was measured from their toes. The vertical and horizontal distances moved were measured using metal tape measures to the nearest 0.01 m and the largest value of three trials was recorded. The mLEFT required the subject to complete one trial of an agility-like course (Figure 2) in the fastest time possible (to the nearest second; (Ellenbecker & Davies, 2001).



1. Forward run (A-C-A)
2. Backward run (A-C-A)
3. Side shuffles (A-B-C-D)
4. Side shuffles (A-D-C-B)
5. Crossover steps (A-B-C-D)
6. Crossover steps (A-D-C-B)
7. 45° angle cuts (A-B-C-D)
8. 45° angle cuts (A-D-C-B)
9. 90° angle cuts (A-D-B)
10. 90° angle cuts (A-B-D)
11. Forward run (A-C-A)
12. Backward run (A-C-A)

Figure 2 The modified lower extremity functional test (mLEFT).

Kinematic data

During landing, each subject's three-dimensional deceleration motion was captured (200 Hz) using the OPTO***TRAK***® 3020 motion analysis system (Northern Digital Inc., Ontario, Canada) located approximately 3 m from a calibrated landing zone. Thirteen infrared light emitting diodes (6 g; 8 mm) were placed on the lower limb to define the foot, leg and thigh segments of the test lower limb. Standard procedures were followed before each trial to enable later computation of the marker coordinates located on each subject's test limb. Raw data was filtered using a forth order zero-phase shift Butterworth filter (cutoff frequency (f_c) = 6 Hz) and then the orientation and motion of the leg and thigh of the landing limb were calculated during each trial from the frame representing initial foot-ground contact (IC) until the frame representing the maximum knee flexion. Knee flexion angle (Figure 3) was also calculated at the frame representing the initial (F_R) and peak resultant force (F_{Rmax}), as these represent the phases of landing which load the ACL the greatest (Prapavessis, 1997).

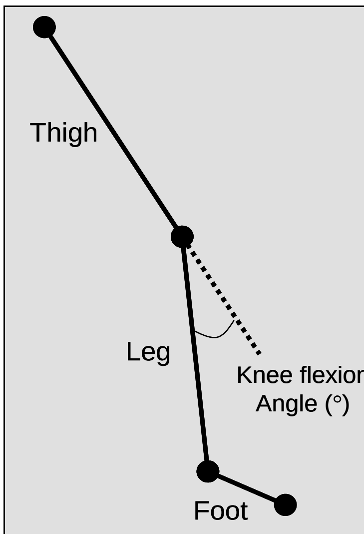


Figure 3 Definition of knee flexion angle.

Kinetic data

The three orthogonal components of the ground reaction forces generated at landing during each trial were quantified using a Kistler Multichannel force platform (Type 9281B, Kistler Instrumente AG Winterthur, Switzerland; 600 mm x 400 mm) connected to a Kistler Multichannel Charge Amplifier (Type 9865A). Force data were sampled (1000 Hz) over 4 s for all successful trials (that is, landing in the middle of the force platform). The ground reaction force signals from four vertical, two anteroposterior and two mediolateral output channels were then summed and scaled to obtain force-time curves as input for calculating the force-time history of the peak resultant force. Figure 4 depicts variables from the force-time history of the peak resultant force that were analysed.

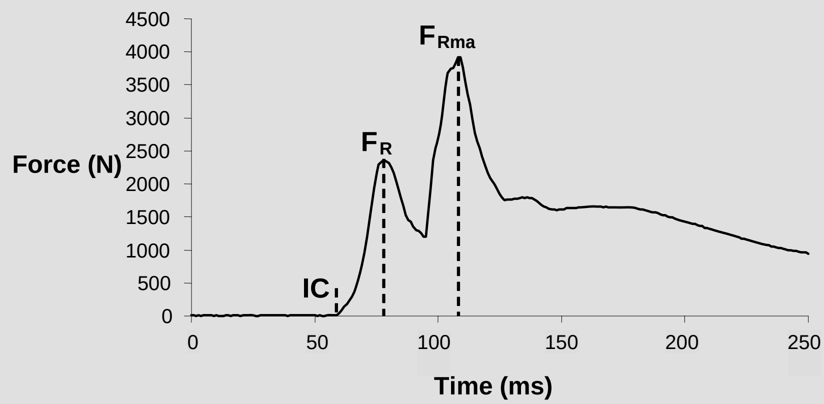


Figure 4 Depiction of a typical force-time history of the peak resultant force (IC = initial contact; F_R = the initial peak resultant force; F_{Rmax} = the maximum peak resultant force).

Electromyographic data

The activation patterns of five lower limb muscles that control knee motion were collected (1000 Hz) using the Telemyo^{TM} 900 electromyography (EMG) system (Noraxon USA Inc., Arizona, USA) for 4 s during each landing task. Following standard skin preparation, muscle activity data for rectus femoris, vastus lateralis, biceps femoris, semimembranosus and the medial head of gastrocnemius were recorded using a bipolar attachment of Blue Sensor (Type M-00-S, Medicotest A/S, Denmark) adhesive silver-silver chloride disposable surface electrodes (impedance < 6 kΩ; CardioMetrics Artifact Eliminator, model CE01, Australia). These muscles were selected because of their superficial location and their involvement in controlling knee motion. The electrodes (inter-detection-surface spacing of 10 mm) were placed over the bellies of the eight muscles of each subject's test limb and each placement was confirmed by palpation while the subject performed isometric contractions. A reference electrode was placed on the medial femoral epicondyle.

Following zero offset removal, raw EMG signals were filtered using a fourth order zero-phase-shift Butterworth high pass filter (f_c = 15 Hz) to eliminate any movement artefact (Winter, 1990). The filtered muscle activity data were then full-wave rectified and low pass filtered (f_c = 20 Hz) and the resultant linear envelopes were screened with a threshold detector (7% of maximum amplitude) to determine the temporal aspects of each muscle burst with respect to initial contact and peak resultant force. The temporal parameters calculated included muscle burst onset, muscle burst offset, magnitude of the peak muscle activity and the time of the peak muscle activity. The calculated results were confirmed by visual inspection to ensure the results truly represented the temporal characteristics of each muscle.

Landing training program

Subjects in the IKS Trained and Placebo Trained groups participated in a six week (Boulton *et al.*, 1984; Caraffa, 1996; Hewett, 1999) landing training program to learn correct landing mechanics, completing three 30 minute training sessions per week. The landing training program was custom-designed to ensure the landing tasks replicated movements performed by athletes in both competition and training in Australia's most popular participation sports. Consequently, landing training progressed from general to specific landing movements incorporating ball skills, surface and footwear changes, gymnasium- and field-based activities, and open and closed skills (Cochrane, 2001; Dvorak, 2000b; Lambson, 1996; Orchard, 1999). The first (session 1, week 1) and final (session 3, week 6) sessions of the landing training program have been included in Appendix A to show how the program developed. Advice on how to land correctly was provided to all subjects participating in landing training in their first training session (Boulton *et al.*, 1984; Hewett, 1999). However, no other feedback, other than the audible feedback from the IKS for the IKS Trained group, was given to the subjects.

Statistical analysis

Means and standard deviations of the kinematic, kinetic and EMG data were calculated to establish the landing mechanics of each subject before and after the six week intervention and after 3 months post-intervention. After confirming normality (Kolmogorov-Smirnov test with Lilliefors' correction) and equal variance (Levene Median test), the pre- and post-intervention data were analysed using an ANOVA design with one between factor (subject group: IKS Trained, Placebo Trained, Control). Then, percentage change data were calculated for each subject to determine the effect of the six week intervention on the dependent variables. One-way ANOVAs were performed on the percentage change data to determine whether there were any significant differences ($p \leq 0.05$) in the kinematic, kinetic and EMG data as a consequence of audible feedback from the IKS within a landing training program.

Results & Discussion

Pre-intervention data

Functional Assessment. No significant between-group differences were identified in the functional assessment tasks pre-intervention (Table 2). Therefore, the groups were considered evenly matched as the subjects displayed similar functional abilities at the start of the study.

Table 2 Mean and statistical data for the functional assessment tasks recorded by the IKS Trained, Placebo Trained and Control subjects pre-intervention (n = 10 per group).

Variable†	IKS Trained	Placebo Trained	Control	*p*-value
MVJ (m)	2.78 (0.24)	2.68 (0.21)	2.71 (0.22)	0.511
MVHD (m)	2.65 (0.22)	2.55 (0.18)	2.55 (0.16)	0.348
MVHND (m)	2.62 (0.24)	2.55 (0.20)	2.56 (0.19)	0.640
MHJ (m)	2.35 (0.30)	2.25 (0.43)	2.23 (0.28)	0.658
MHHD (m)	1.98 (0.28)	1.87 (0.37)	1.93 (0.20)	0.664
MHHND (m)	1.95 (0.24)	1.85 (0.39)	1.89 (0.24)	0.733
mLEFT (m)	66.3 (7.7)	67.6 (7.8)	70.9 (8.4)	0.379

† MVJ = maximal vertical jump; MVHD = maximal vertical hop, dominant limb; MVHND = maximal vertical hop, non-dominant limb; MHJ = maximal horizontal jump; MHHD = maximal horizontal hop, dominant limb; MHHND = maximal horizontal hop, non-dominant limb; mLEFT = modified lower extremity functional test.

Knee Flexion Angle. Mean (standard deviation) and statistical data pertaining to the knee flexion angle calculated during the dynamic deceleration task pre-intervention for each group are displayed in Table 3. There were no significant differences between the three groups for knee flexion angle calculated at initial contact, peak resultant force or maximum knee flexion. Therefore, the three groups were evenly matched with respect to knee flexion angle during the landing task.

Table 3 Knee flexion angle results for the IKS Trained, Placebo Trained and Control subjects pre-intervention (n = 10 per group).

Variable†	IKS Trained	Placebo Trained	Control	*p*-value
Knee flexion at IC (°)	9.2 (4.2)	11.0 (6.0)	11.4 (6.1)	0.346
Knee flexion at F_{Rmax} (°)	17.1 (4.9)	16.7 (6.2)	18.7 (9.7)	0.794
Maximum knee flexion (°)	65.9 (12.3)	72.7 (21.1)	71.8 (22.5)	0.646
IC to maximum knee flexion (ms)	55 (17)	58 (20)	65 (22)	0.487

† IC = initial contact; F_{Rmax} = peak resultant force.

Steele (1990) suggested that to decrease potential for injury to the musculoskeletal system, athletes performing dynamic landings, similar to the task performed in the present study, should land with their knees flexed 17º at initial contact and 40º at the peak resultant ground reaction force. In the present study, subjects in all groups recorded knee flexion angles that were 35% and 55%, respectively below the suggestions of Steele (1990). Instead, the knee flexion angles displayed at initial contact and at peak resultant force in the present study (Table 3) were similar to those reported previously for healthy subjects landing dynamically in single-limb stance (Cowling *et al.*, 2003; Hewett *et al.*, 1996; Madigan & Pidcoe, 2003; Steele, 1997). The values of maximum knee flexion were similar to those reported by Decker *et al.* (2003) when male and female recreational athletes performed a 60 cm drop landing (63° - 76°). Furthermore, the data presented in the present study were marginally less than those reported by Sacli *et al.* (2004) for national university first league male volleyball players performing spike and block landings from 40 cm and 60 cm heights (72° - 88°), although greater than those reported by Madigan & Pidcoe (2003) when healthy, physically active males performed a single leg landing from a 25 cm height (43°). Accordingly, as the landing task performed in the present study was directed horizontally rather than vertically and not as controlled as these aforementioned studies, variation in the results was anticipated. However, as the ACL is most susceptible to musculoskeletal injury within the range of 20° to 30° knee flexion (Hutchinson & Ireland, 1995), all subjects in the present study were at equal risk of sustaining an ACL injury by performing the landing task with a more extended lower limb.

Ground Reaction Forces. The average peak vertical and anteroposterior ground reaction forces generated in the present study ranged from 4.2 to 4.6 times body weight and 2.4 to 2.8 times body weight, respectively (Table 4). These data were similar in magnitude to data recorded in other studies involving landings (McNair & Marshall, 1994a; Prapavessis & McNair, 1997; Steele & Milburn, 1987). Furthermore, the timing of the ground reaction forces were similar to those reported by Decker *et al.* (2003) for subjects performing drop jump landings from a 60 cm height (F_R = 10 - 11 ms; F_{Rmax} = 40 - 44 ms) and Hass *et al.* (2003) when subjects performed stride jump landings onto a single limb (F_{Rmax} = 47 ms). No significant between-group differences were found in the ground reaction force variables generated during the pre-training landing task in the present study (Table 4). Therefore, each group was again considered evenly matched with respect to the ground reaction forces generated during the landing task in the present study.

Table 4 Ground reaction force results for the IKS Trained, Placebo Trained and Control subjects pre-intervention (n = 10 per group).

Variable†	IKS Trained	Placebo Trained	Control	*p*-value
Peak F_V (BW)	4.5 (0.8)	4.6 (0.9)	4.4 (0.9)	0.851
Peak F_{AP} (BW)	2.5 (0.7)	2.6 (0.6)	2.5 (0.6)	0.862
Initial F_R (BW)	3.1 (0.9)	3.0 (1.0)	3.4 (0.7)	0.405
Maximum F_R (F_{Rmax}; BW)	4.9 (0.9)	5.2 (0.9)	4.9 (1.2)	0.747
IC to peak F_V (ms)	37 (8)	34 (8)	31 (7)	0.203
IC to peak F_{AP} (ms)	37 (6)	34 (5)	35 (6)	0.602
IC to F_R (ms)	19 (6)	17 (2)	18 (4)	0.444
IC to F_{Rmax} (ms)	38 (6)	36 (5)	36 (8)	0.661

† All magnitude data were normalised to body weight (BW); IC = initial contact; F_V = vertical ground reaction force; F_{AP} = anterior-posterior ground reaction force (braking force); F_R = initial peak resultant force; F_{Rmax} = maximum resultant force.

Electromyographic Data. A summary of the mean (standard deviation) data pertaining to the muscle activation patterns displayed by subjects from each group is presented in Table 5. One-way ANOVA results revealed two significant between-ground differences in the muscle activation patterns displayed by the subjects at the start of the study. That is, the IKS Trained subjects activated VL significantly earlier than the Placebo Trained subjects with respect to initial contact (q = 3.439; p =0.053) and peak resultant force (q = 3.551; p =0.044) during the initial data collection session (Table 5).

All the muscles examined in the present study consistently showed onset times before initial contact, suggesting pre-programmed muscle activity (Andriacchi, 1990), as would be anticipated in a subject group skilled in performing landing movements (McKinley & Pedotti, 1992). This pre-programmed muscle activation strategy encompassed hamstring muscle activation followed by quadriceps and gastrocnemius muscle activation (Table 5). Furthermore, peak hamstring activity occurred *before* initial contact and the peak resultant force, whereas peak quadriceps muscle activity occurred *after* these same events within the landing task. This muscle synchrony pattern has been observed in previous studies in which subjects have performed similar landing tasks (Cowling *et al.*, 1998; Cowling *et al.*, 2003; Steele, 1997; Steele & Brown, 1999) and has been suggested by Kain *et al*. (1988) to provide optimal protection to the ACL. That is, the hamstring muscles have sufficient time to provide a posterior tibial drawer force to counteract the later anterior tibial translation and rotation induced by the quadriceps muscles. Furthermore, this pre-activation is suggested to raise the activation stage of the reflex system in order to withstand the high force development which takes place immediately after initial contact (Aura & Viitasalo, 1989). After accounting for electromechanical delay that can vary between 20 ms and 100 ms (Zhou *et al.*, 1995), it has been suggested that the posterior drawer force created by the peak hamstring and gastrocnemius muscles may be synchronous with the peak braking forces generated during landing. Furthermore, the peak quadriceps muscle activity which occurred after the peak resultant force in the present study is suggested to create a knee extension moment at initial contact, preventing the loaded knee joint from collapsing upon landing (Winter, 1991). Despite the two significant muscle activation findings, subjects in the IKS Trained, Placebo Trained and Control groups in the present study appeared relatively evenly matched in their performance of the landing task, suggesting that all were skilled at performing the landing movements as stipulated by the subject inclusion criteria.

Table 5 Pre-intervention results for the muscle activation patterns generated at landing by subjects in the IKS Trained, Placebo Trained and Control groups (n = 10 per group).

Variable†	Muscle	IKS Trained	Placebo Trained	Control	*p*-value
Muscle burst duration (ms)	RF	304 (109)	257 (44)	312 (63)	0.179
	VL	297 (99)	237 (43)	264 (66)	0.140
	BF	180 (46)	185 (50)	191 (35)	0.829
	S	166 (18)	160 (46)	186 (50)	0.303
	G	199 (70)	176 (66)	220 (59)	0.266
Muscle burst onset time to IC (ms)‡	RF	-62 (33)	-59 (33)	-51 (21)	0.679
	VL	-109 (45)	-73 (36)	-78 (28)	0.046*
	BF	-147 (27)	-118 (49)	-124 (36)	0.164
	S	-142 (19)	-130 (40)	-138 (42)	0.692
	G	-90 (35)	-83 (31)	-77 (27)	0.641
IC to muscle burst peak time (ms)‡	RF	78 (20)	60 (19)	80 (30)	0.099
	VL	65 (24)	56 (39)	71 (32)	0.543
	BF	-62 (28)	-30 (56)	-37 (50)	0.212
	S	-57 (19)	-49 (55)	-31 (42)	0.355
	G	-7 (39)	-9 (25)	15 (37)	0.202
Muscle burst onset time to F_{Rmax} (ms)§	RF	-99 (34)	-95 (33)	-87 (19)	0.617
	VL	-147 (43)	-109 (37)	-113 (31)	0.037*
	BF	-184 (27)	-154 (47)	-160 (35)	0.117
	S	-180 (24)	-167 (41)	-173 (44)	0.688
	G	-125 (30)	-119 (30)	-113 (28)	0.610
Muscle burst peak time to F_{Rmax} (ms)§	RF	41 (17)	24 (18)	44 (31)	0.084
	VL	27 (24)	20 (39)	35 (35)	0.552
	BF	-99 (27)	-66 (54)	-72 (50)	0.175
	S	-94 (22)	-86 (56)	-66 (42)	0.299
	G	-45 (37)	-45 (28)	-20 (34)	0.138

† IC = initial contact; F_{Rmax} = maximum resultant force.
* Indicates a significant between-group difference for a given variable.
‡ A negative value indicates that the muscle burst variable occurred before IC.
§ A negative value indicates that the muscle burst variable occurred before F_{Rmax}.

Post-intervention data

Functional Assessment. Although there were no significant between-group differences in the raw functional assessment data at the completion of the six week intervention, when comparing the percentage change data, the Placebo Trained group recorded a significant improvement in their maximal horizontal hop on their non-dominant lower limb compared to both the IKS Trained (q = 4.501; p = 0.010) and Control (q = 3.706; p = 0.037) groups (Table 6). However, high variation was found in the percentage change data, as evidenced by the high standard deviations (Table 6), with subjects from all groups displaying positive (improvement) and negative (decline in ability) changes over the six weeks (Figure 5). Although one may expect the subjects in both landing training groups to improve their functional performance relative to the control subjects, it must be remembered that the training program focused on correct *landing* technique rather than jump performance *per se*. It is therefore speculated that factors external to the research study may have influenced each subject's functionality more so that the landing training program. Examination of the activity diaries confirmed that individual subjects both commenced and ceased training programs and competitions for their individual sports during the time that they were involved in the research study. Consequently, although many individual improvements in landing control were evident, the landing training program, whether completed receiving feedback or not receiving feedback, did not influence the functionality of subjects within a group, as measured using the simple field-based tests.

Table 6 Mean and statistical post-intervention and percentage change data for the functional assessment tasks recorded by subjects in the IKS Trained, Placebo Trained and Control groups (n = 10 per group).

Variable†	IKS Trained	Placebo Trained	Control	*p*-value
Post-Intervention Data				
MVJ (m)	2.70 (0.23)	2.70 (0.21)	2.72 (0.23)	0.984
MVHD (m)	2.59 (0.18)	2.56 (0.17)	2.58 (0.17)	0.945
MVHND (m)	2.58 (0.21)	2.57 (0.17)	2.57 (0.18)	0.984
MHJ (m)	2.25 (0.22)	2.22 (0.43)	2.28 (0.31)	0.909
MHHD (m)	1.95 (0.30)	1.97 (0.39)	1.96 (0.22)	0.983
MHHND (m)	1.89 (0.28)	1.99 (0.40)	1.92 (0.28)	0.811
mLEFT (m)	62.8 (5.0)	65.9 (8.9)	67.3 (9.4)	0.501
Percentage Change Data				
MVJ (%)	-0.2 (2.2)	0.9 (1.3)	0.2 (1.4)	0.381
MVHD (%)	1.1 (1.1)	0.6 (1.8)	1.2 (2.7)	0.774
MVHND (%)	1.4 (1.6)	1.3 (1.0)	0.3 (1.0)	0.088
MHJ (%)	-0.9 (4.7)	-2.2 (8.2)	2.3 (4.8)	0.245
MHHD (%)	1.0 (6.4)	4.8 (8.3)	2.1 (3.9)	0.420
MHHND (%)	-0.2 (4.0)	8.3 (7.9)	1.8 (4.0)	0.008*
mLEFT (%)	-3.8 (6.5)	-3.5 (4.9)	-5.2 (3.8)	0.702

† MVJ = maximal vertical jump; MVHD = maximal vertical hop, dominant limb; MVHND = maximal vertical hop, non-dominant limb; MHJ = maximal horizontal jump; MHHD = maximal horizontal hop, dominant limb; MHHND = maximal horizontal hop, non-dominant limb; mLEFT = modified lower extremity functional test.
* indicates a significant difference.

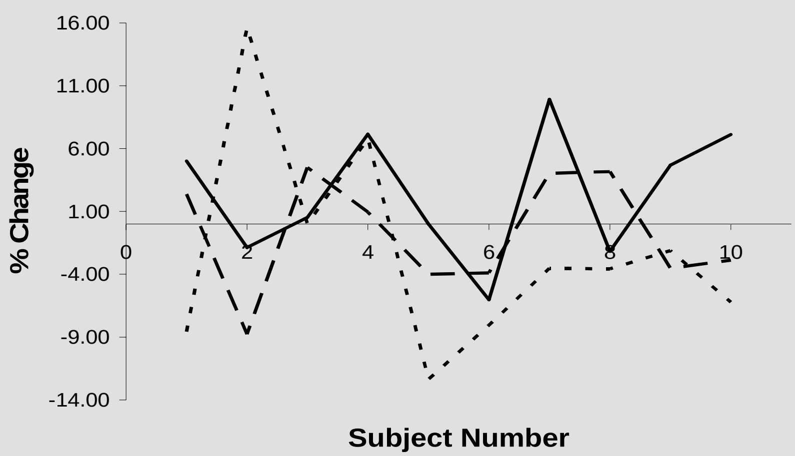


Figure 5 Percentage change data for the maximal horizontal jump for the IKS Trained (—), Placebo Trained (·····) and Control (---) subjects.

Knee Flexion Angle. There were no significant between-group differences in the post-intervention raw data for any of the knee flexion variables when the subjects performed the landing task (Table 7). However, although not statistically significant, relatively large differences were evident in the percentage changes displayed by the three subject groups in the mean maximum knee flexion data from pre- to post-intervention. For example, the IKS Trained group increased their maximum knee flexion angle from pre- to post-intervention an average of 8° (Table 3 and Table 7). In contrast, neither the Placebo Trained group nor the

Control group increased their maximum knee flexion over the six weeks. In fact, both these two latter groups displayed a reduction in their average maximum knee flexion angles over the six weeks by 2° and 5°, respectively.

Table 7 Post-intervention and percentage change knee flexion angle results for subjects in the IKS Trained, Placebo Trained and Control groups (n = 10 per group).

Variable†	IKS Trained	Placebo Trained	Control	*p*-value
Post-Intervention				
Knee flexion at IC (°)	10.6 (5.5)	11.1 (6.2)	9.3 (8.5)	0.842
Knee flexion at F_{Rmax} (°)	17.3 (6.7)	20.5 (7.8)	14.7 (6.8)	0.194
Maximum knee flexion (°)	73.5 (13.9)	70.8 (18.1)	66.9 (18.5)	0.707
IC to maximum knee flexion (ms)	79 (19)	68 (19)	63 (23)	0.296
Percentage Change Data				
Knee flexion at IC (%)	14.0 (46.5)	-22.5 (39.2)	-10.6 (36.3)	0.206
Knee flexion at F_{Rmax} (%)	5.1 (28.4)	-2.9 (40.9)	-11.3 (36.6)	0.619
Maximum knee flexion (%)	7.1 (22.6)	-6.0 (12.8)	-3.6 (21.9)	0.383
IC to maximum knee flexion (%)	38.5 (39.7)	23.4 (44.4)	2.0 (29.8)	0.125

† IC = initial contact; F_{Rmax} = peak resultant force.

Hewett *et al*. (1999) reported that, after completing a six week landing training program which successfully decreased the incidence of ACL injuries in soccer, volleyball and basketball, female high school volleyball players were found to increase their maximum knee flexion by only 3° and the male high school volleyball players recorded no change in maximal knee flexion (Hewett *et al.*, 1996). Therefore, the 8° mean change in knee flexion angle following training in the present study is considered a relatively large and positive change, particularly considering the subjects were all skilled and experienced athletes who would be expected to display relatively well practiced and ingrained motor patterns that are difficult to change. The result also confirms subjective feedback from the IKS Trained subjects who felt they bent their knees more and had greater stability when performing landing movements after participating in the landing training program. Interestingly, both the Placebo Trained and Control groups decreased their knee flexion, despite the Placebo Trained subjects having participated in the same landing training program as the IKS Trained subjects (Table 7). This finding would appear to support the notion that participating in landing training programs without immediate feedback pertaining to knee flexion angle does not guarantee improved knee flexion. It is acknowledged that the between-group differences in the percentage change knee flexion data were not statistically significant. It is postulated that any such statistical significance was somewhat masked by the extremely high variation within each group, which is clearly evident from the large standard deviations (Table 7).

As the subjects in the present study were all skilled in the landing movement, the high variability in the knee flexion data was not anticipated. However, this variability indicates that the subjects used individual strategies to land and responded differently to the six week intervention program. Consequently, the statistical powers were lower than the required 80% and therefore the lack of statistically significant findings should be interpreted cautiously. High subject variability combined with high subject drop-out and difficulties in subject recruitment are problems typically inherent in time-intensive human intervention training studies. Despite the low statistical power and high subject variability, the mean percentage change data supported the hypotheses in that, following the landing training program using the IKS, the IKS Trained subjects displayed greater knee flexion when landing from a jump with minor reductions in the forces generated at landing (Table 8). Interestingly, compared to the Control group who showed no change, both the IKS Trained and Placebo Trained groups increased the time they took until they reached maximum knee flexion (Table 7). Increased maximum knee flexion as well as increased time to maximum knee flexion may allow subjects greater control when reducing the downward momentum acquired during the flight of a jump, providing a softer landing, particularly as the knee has been identified as the primary shock absorber during landing (Decker *et al.*, 2003).

Ground Reaction Forces. The mean (standard deviation) and statistical data pertaining to the ground reaction forces generated at landing by the subjects in each group post-intervention, as well as the mean percentage change data, are displayed in Table 8. There were no significant differences in the mean post-intervention ground reaction force data, although a strong trend was evident towards the Control subjects generating greater peak vertical ground reaction forces compared to the IKS Trained and Placebo Trained subjects at the post intervention testing session.

Table 8 Post-intervention and percentage change data for the ground reaction forces calculated at landing for subjects in the IKS Trained, Placebo Trained and Control groups (n = 10 per group).

Variable†	IKS Trained	Placebo Trained	Control	*p*-value
Post-Intervention Data				
Peak F_V (BW)	4.3 (1.1)	4.5 (0.6)	5.2 (0.9)	0.059
Peak F_{AP} (BW)	2.5 (0.6)	2.7 (0.8)	3.0 (0.8)	0.363
Initial F_R (BW)	3.0 (0.7)	2.5 (0.9)	3.1 (0.9)	0.326
Maximum F_R (BW)	4.8 (1.1)	5.0 (0.7)	5.6 (1.1)	0.140
IC to peak F_V (ms)	36 (11)	37 (8)	33 (6)	0.641
IC to peak F_{AP} (ms)	39 (7)	34 (7)	32 (9)	0.195
IC to F_{R1} (ms)	17 (4)	17 (2)	16 (3)	0.872
IC to F_{Rmax} (ms)	40 (7)	37 (6)	35 (7)	0.302
Percentage Change Data				
Peak F_V (%)	-2.8 (11.8)	-3.5 (15.0)	19.0 (21.4)	0.008*
Peak F_{AP} (%)	2.2 (15.4)	0.7 (32.3)	21.9 (37.5)	0.242
Initial F_R (%)	3.8 (15.2)	-8.6 (22.2)	-10.9 (20.0)	0.263
Maximum F_R (%)	-1.2 (15.2)	-5.8 (15.4)	16.5 (21.5)	0.021*
IC to peak F_V (%)	-4.6 (19.0)	2.1 (24.2)	10.5 (27.4)	0.411
IC to peak F_{AP} (%)	1.2 (15.3)	0.7 (19.0)	-7.9 (20.7)	0.482
IC to F_{R1} (%)	-1.9 (22.2)	2.8 (16.9)	-3.9 (12.7)	0.664
IC to F_{Rmax} (%)	4.3 (13.6)	2.7 (21.8)	0.7 (19.6)	0.920

† F_V = vertical ground reaction force, F_{AP} = anterior-posterior GRF (braking force); F_{R1} = initial resultant ground reaction force; F_{Rmax} = maximum resultant ground reaction force;
* indicates a significant difference.

When comparing the percentage change data it became evident that the Control subjects generated significantly greater peak vertical ground reaction forces compared to both the IKS Trained (q = 3.904; p = 0.027) and the Placebo Trained (q = 4.283; p = 0.015) subjects (Table 8). The increased peak vertical ground reaction force contributed to the Control subjects recording a significantly greater peak resultant force compared to the Placebo Trained subjects (q = 4.028; p = 0.022; Table 8). It is suggested that the extra confidence gained by the Control subjects during their post-intervention testing relative to the initial pre-intervention testing, attributed to being more familiar with the testing protocols and venue, may have led to these increased ground reaction force variables. Consequently, the negative percentage change data calculated for the IKS Trained and Placebo Trained subjects indicated that these subjects displayed a training effect leading to reduced ground reaction forces (Table 8). That is, the landing training program was successful in teaching the athletes to reduce the forces that they generated at landing, irrespective of the feedback received during training.

These decreased ground reaction forces may have in part resulted from the increased knee flexion displayed by these two groups (Table 7), as lower force landings have been associated with more flexed joints at landing (Mizrahi & Susak, 1982), a softer, quieter landing movement (DeVita & Skelly, 1992; McNair *et al.*, 2000), reduced anterior tibial acceleration (McNair & Marshall, 1994b) and decreased incidence of knee injury (Dufek & Bates, 1991).

Electromyographic Data. Data describing the effects of the six week intervention on muscle synchrony are summarised in Table 9. Although there were no significant between-group effects on any of the post-intervention raw muscle synchrony data, there was one significant between-group finding when examining the percentage change data pertaining to muscle synchrony (Table 10). That is, the Placebo Trained group recorded a positive change towards a significantly longer gastrocnemius muscle burst duration compared to the Control group (q = 3.889; p = 0.029) with a similar strong trend compared to the IKS Trained group (q = 3.469; p = 0.054). Interestingly, both the Control group and the IKS Trained group displayed negative changes towards shorter muscle burst durations post-intervention (Table 10). The longer gastrocnemius muscle burst duration appears to have resulted from the Placebo Trained subjects displaying an earlier gastrocnemius muscle burst onset with respect to initial contact compared to the IKS Trained and Control subjects (Table 10).

Table 9 Post-intervention results for the muscle activation patterns displayed at landing by subjects in the IKS Trained, Placebo Trained and Control groups (n = 10 per group).

Variable	Muscle	IKS Trained	Placebo Trained	Control	*p*-value
Muscle burst duration (ms)	RF	257 (90)	226 (70)	250 (37)	0.579
	VL	265 (107)	252 (83)	265 (50)	0.918
	BF	174 (22)	176 (49)	178 (43)	0.977
	S	198 (81)	194 (46)	202 (62)	0.958
	G	164 (51)	196 (54)	175 (54)	0.459
Muscle burst onset time to IC (ms) †	RF	-68 (34)	-82 (56)	-74 (33)	0.763
	VL	-100 (39)	-94 (34)	-95 (35)	0.941
	BF	-115 (51)	-98 (39)	-114 (34)	0.613
	S	-118 (35)	-116 (43)	-126 (35)	0.837
	G	-106 (46)	-131 (63)	-80 (42)	0.099
IC to muscle burst peak time (ms) †	RF	71 (32)	33 (76)	66 (48)	0.298
	VL	5 (60)	17 (91)	28 (33)	0.756
	BF	-24 (69)	-13 (64)	-23 (47)	0.903
	S	-55 (59)	-56 (62)	-60 (66)	0.981
	G	-28 (32)	-40 (24)	-11 (39)	0.168
Muscle burst onset time to F_{Rmax} (ms) ‡	RF	-108 (31)	-120 (55)	-110 (33)	0.804
	VL	-139 (40)	-131 (37)	-131 (37)	0.871
	BF	-155 (50)	-135 (39)	-150 (36)	0.574
	S	-159 (34)	-153 (45)	-162 (35)	0.881
	G	-146 (47)	-167 (60)	-116 (44)	0.098
Muscle burst peak time to F_{Rmax} (ms) ‡	RF	31 (30)	-4 (76)	29 (48)	0.319
	VL	5 (60)	17 (91)	28 (33)	0.756
	BF	-64 (68)	-50 (63)	-59 (48)	0.876
	S	-55 (59)	-56 (62)	-60 (66)	0.981
	G	-68 (31)	-76 (22)	-47 (38)	0.129

* denotes a significant difference between test conditions for a given variable.
† a negative value indicates that the muscle burst variable occurred before IC.
‡ a negative value indicates that the muscle burst variable occurred before FRmax.

Apart from this one significant between-group difference, there were no other significant effects of the intervention program on any of the muscle synchrony data. However, again there was high variation within the data sets, as evidenced by the high standard deviations in both the descriptive post-intervention (Table 9) and percentage change data (Table 10). This high variation suggests that the subjects responded differently to the training programs in terms of the manner in which they recruited their lower limb muscles in preparation to land. As subjects in the present study were injury-free throughout the study, it is speculated that this variability represents each subject using muscle activity patterns that may have been optimal for them to control their lower limbs during landing.

It is possible that the landing training program may have allowed the subjects to develop their lower limb muscle strength such that they recruited stronger muscles to provide greater lower limb stability during landing. For example, Hewett *et al*. (1996) found that peak hamstring isokinetic torque increased after a six week training program in high school volleyball players. The stronger muscles of these subjects were thought to influence the joint moments surrounding the knee, providing greater stabilisation of the knee joint and allowing the hamstring muscles to play a greater role in joint compression and restraint of anterior tibial translation to decrease the anterior shear forces, greatly reducing load on the ACL (Tibone *et al*., 1986). Further research pertaining to the effects of landing training programs on muscle strength and, in turn, injury rates are therefore recommended.

Table 10 Percentage change data for the muscle activation patterns generated at landing by subjects in the IKS Trained, Placebo Trained and Control subjects (n = 10 per group).

Variable	Muscle	IKS trained	Placebo trained	Control	*p*-value
Muscle burst duration (%)	RF	-5.0 (51.1)	-12.5 (30.6)	-17.0 (20.1)	0.757
	VL	-5.5 (30.6)	7.3 (35.2)	8.2 (40.7)	0.683
	BF	1.9 (37.6)	-2.2 (37.3)	-3.0 (30.0)	0.951
	S	15.1 (38.7)	31.2 (44.7)	6.9 (26.1)	0.350
	G	-15.7 (31.1)	20.6 (35.5)	-17.1 (25.3)	0.021*
Muscle burst onset time to IC (%) †	RF	33.1 (88.4)	77.2 (150.1)	59.6 (86.0)	0.715
	VL	1.7 (44.9)	56.0 (69.9)	29.9 (53.0)	0.158
	BF	-21.1 (30.5)	-6.0 (40.9)	-0.1 (47.9)	0.550
	S	-16.6 (25.1)	7.3 (75.4)	-1.2 (25.4)	0.599
	G	43.3 (83.0)	75.0 (128.2)	5.8 (46.3)	0.245
IC to muscle burst peak time (%) †	RF	-1.2 (52.3)	-58.8 (185.8)	-8.3 (64.4)	0.527
	VL	-5.8 (117.8)	-31.8 (216.0)	45.6 (172.3)	0.600
	BF	82.7 (363.6)	132.8 (502.0)	-95.6 (105.0)	0.322
	S	-86.0 (138.1)	-64.0 (139.6)	-155.6 (454.8)	0.773
	G	-90.2 (212.1)	84.1 (201.9)	15.6 (282.7)	0.357
Muscle burst onset time to F_{Rmax} (%) ‡	RF	19.0 (36.7)	37.5 (83.9)	29.3 (39.9)	0.801
	VL	0.7 (29.1)	31.8 (46.8)	20.1 (34.1)	0.240
	BF	-15.0 (22.2)	-6.6 (30.6)	-1.6 (36.1)	0.652
	S	-12.4 (19.6)	2.0 (54.8)	-1.8 (18.7)	0.698
	G	21.9 (46.1)	46.7 (79.0)	3.7 (32.1)	0.236
Muscle burst peak time to F_{Rmax} (%) ‡	RF	20.9 (168.3)	178.4 (1274.4)	91.6 (473.8)	0.918
	VL	-209.0 (328.8)	477.7 (1816.4)	-43.0 (185.0)	0.375
	BF	-44.0 (86.2)	-68.3 (137.6)	320.8 (1301.0)	0.486
	S	-44.5 (62.8)	-73.2 (110.7)	-67.1 (148.0)	0.864
	G	62.2 (139.2)	-35.2 (259.3)	47.0 (241.3)	0.621

* denotes a significant difference between test conditions for a given variable.
† a negative value indicates that the muscle burst variable occurred before IC.
‡ a negative value indicates that the muscle burst variable occurred before F_{Rmax}.

Subjective feedback

Those subjects who participated in the landing training program provided general subjective feedback suggesting that, at the completion of the landing training program:

- their lower limbs felt stronger and were more "toned",
- they felt more stable when performing landing movements,
- they felt they had learnt to land softly,
- they felt they had greater upper body control when performing landing movements, and
- they felt more aware of their body in space when performing landing movements on different surfaces.

As many of these subjective parameters were not measured biomechanically in the present study it is recommended that future studies assessing the effectiveness of landing training programs also quantify parameters such as lower limb muscle strength, stability during landing (possibly by centre of gravity excursions), upper body motion and kinaesthetic awareness.

Those subjects who participated in the IKS Trained group and received audible feedback about their knee flexion angle during training suggested that:

- they "bent their knee more" when they landed from a jump, which reduced the impact of landing,
- they thought the concept of the IKS was "great", although they became annoyed when the sleeve malfunctioned, requiring them to repeat activities,
- they were pleased that they could determine the correct amount of knee flexion required even when the audible feedback from the IKS did not sound and were able to tell the instructor that the IKS was not functioning properly, i.e. that they were bending too far or not enough,
- they were surprised that even during fast and repetitive landing movements that they were able to achieve the correct knee flexion angle for the IKS to emit its audible tone, and
- they felt greater lateral knee stability at the completion of the landing training program.

The subjective feedback received from the IKS Trained participants therefore appeared to support the concept of landing training in general as well as the benefits of landing training with audible feedback pertaining to knee flexion angle.

Limitations of the study

Limitations, which may have affected the outcome of the present study, are listed below:

a) *Subject recruitment* was difficult due to the extensive time commitment required by the subjects allocated to the two training arms of the study. The researchers originally approached numerous sporting teams involved in landing sports such as volleyball, netball, basketball and the various football codes. However, many professional athletes were not given permission to participate in an "unproven" experimental program and/or were unavailable as the scheduled landing training program did not coincide with an appropriate time within their season to allow the athletes to commit to the study. Although the coaches of many amateur teams encouraged their athletes to participate in the study, the time commitment again proved a barrier for many of these volunteer athletes. Therefore, subjects recruited for the study came from varied backgrounds and, although skilled in their respective sports, this skill level may have varied between sports. Furthermore, individual subject recruitment led to a smaller than anticipated subject sample size and a higher than anticipated subject drop out rate in the present study. This high drop out rate led to poor data recovery at 3 months post-intervention.

b) *Random group assignment* led to potential subjects withdrawing their consent before involvement in the study. That is, some interested participants would only participate if they could be assigned to a particular group. As this could lead to experimental bias, subjects were only accepted into the study if they agreed to be randomly allocated to any of the three groups.

c) *Timetabling* of training sessions within the Biomechanics Research Laboratory were completed on a one-to-one basis to ensure uniformity in training. However, by the logistics of scheduling so many individual training sessions meant that the study had to be completed in two portions and consequently, subjects were assessed at different times of the year, in different sporting and environmental seasons.

d) *Contamination* of subject groups may have occurred due to media attention the IKS received prior to and during the study. Furthermore, although timetabling was completed in an attempt to separate subjects in the IKS Trained and the Placebo Trained groups, some overlap was unavoidable as training sessions were timetabled according to subject availability.

e) *Subject activity* outside the research study could not be controlled and throughout their involvement, subjects in all groups moved through pre-season conditioning, in-season competition and post-season recovery, depending on their specific sport. Furthermore, involvement in the research study and/or landing training program facilitated some subjects increasing their activity levels despite being encouraged not to change their lifestyle. This outside activity sometimes coincided with timetabled training sessions such that subjects did not adhere to recommendations of not completing heavy training sessions on the days of their landing training sessions.

f) The *landing training program* was specifically designed and implemented by experienced research personnel. However, this program has not been proven to reduce the incidence of ACL injuries in the field.

g) The IKS was set to a *knee flexion angle* of approximately 35° based on the recommendation of Steele (1990). This knee flexion angle may not be the most optimal angle to train subjects to achieve.

h) Although the *IKS* was found to be valid and reliable in a previous study with basic landing activities over a 30 minute period, in the present study, the sensor and wiring sometimes reacted to sweat and humidity, requiring repairs. These stoppages within training sessions may have affected the results obtained for subjects involved in the IKS Trained group.

Conclusions & Future Directions

Dynamic deceleration movements, such as the one performed in the present study, are known to increase ACL loading and have been identified as a mechanism of ACL rupture. It has been suggested that teaching athletes to flex their knees more at landing may reduce their risk of ACL injury. However, increasing the knee flexion of skilled athletes experienced at performing such an abrupt horizontal movement is known to be “challenging” due to their ingrained motor patterns. Therefore, interventions that can achieve increases in knee flexion during such a task, particularly with experienced athletes whose movement patterns are relatively “ingrained”, are keenly sort for ACL injury prevention initiatives.

In the present study landing training was proven successful in terms of teaching skilled athletes to reduce the forces that they generated at landing, irrespective of the feedback received during training. However, providing skilled athletes with immediate feedback about their knee flexion during a six week landing training program using the IKS, tended to assist them to increase their knee flexion angle more so than skilled athletes who participated in a similar landing training program but without any feedback, although the results were not conclusive due to low statistical power. Furthermore, the athletes responded in a variety of different ways to the training programs, irrespective of feedback, in terms of the manner in which they recruited their lower limb muscles in preparation to land. As subjects in the present study were injury-free throughout the study, it was speculated that this variability represented each subject using muscle activity patterns that may have been optimal for them to control their lower limbs during landing.

As the results of the present study pertaining to the effects of immediate feedback on increasing knee flexion during dynamic landing tasks are inconclusive, further research is recommended to answer the following questions:

a) Can use of the IKS within a landing training program change the knee flexion angle displayed by a larger and more constrained subject sample during landing movements?
b) If the knee flexion angle can be modified, what is the optimal knee flexion angle that should be obtained during landing?
c) Can changes in knee flexion angle made in the gymnasium or laboratory be transferred to the field?
d) Do changes in knee flexion angle decrease the incidence of ACL injuries in sports that require landing movements?

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Appendix A
Excerpt from Landing Training Program

Landing Training Program **Week 1: Session 1**

A. Introduction (2 mins)
- Why are we doing the training?
- Why focus on non-contact landing injuries?

B. Good Landing Technique (3 mins and throughout)
- What is a good landing?
- What should they focus on when performing landing training activities?

C. Warm Up (5 mins)
- Quadriceps, hamstrings, triceps surae, hip flexors, gluteals, adductor stretches

Activity	TO	Land	Condition	Surface	Reps	Speed	Effort	Focus
Dual limb								
Knee bend	2	2	Heels on	Hard	5	Slow	Min	Technique
Knee bend	2	2	Heels off	Hard	5	Slow	Min	Technique
Knee bend	2	2	Eyes closed	Hard	5	Slow	Min	Technique
Vertical jump	2	2	Same level	Hard	5	Slow	Min	Technique
Step-off forward	2	2	30 cm	Hard	10	Slow	Min	Technique
Broad jump	2	2	Same level	Hard	10	Slow	Min	Technique
Right limb								
Knee bend	1	1	Heels on	Hard	5	Slow	Min	Technique
Knee bend	1	1	Heels off	Hard	5	Slow	Min	Technique
Knee bend	1	1	Eyes closed	Hard	5	Slow	Min	Technique
Left limb								
Knee bend	1	1	Heels on	Hard	5	Slow	Min	Technique
Knee bend	1	1	Heels off	Hard	5	Slow	Min	Technique
Knee bend	1	1	Eyes closed	Hard	5	Slow	Min	Technique
Right limb								
Vertical hop	1	1	Same level	Hard	5	Slow	Min	Technique
Broad hop	1	1	Same level	Hard	10	Slow	Min	Technique
Step-off forward	2	1	30 cm	Hard	10	Slow	Min	Technique
Bound forward	2	1	Same level	Hard	10	Slow	Min	Technique
Left limb								
Vertical hop	1	1	Same level	Hard	5	Slow	Min	Technique
Broad hop	1	1	Same level	Hard	10	Slow	Min	Technique
Step-off forward	2	1	30 cm	Hard	10	Slow	Min	Technique
Bound forward	2	1	Same level	Hard	10	Slow	Min	Technique

NB: Slow = hold for 2 s upon landing; L = left; R = right

D. Cool Down (5 mins)
- Quadriceps, hamstrings, triceps surae, hip flexors, gluteals, adductor stretches

A. Warm Up (5 mins)

- Quadriceps, hamstrings, triceps surae, hip flexors, gluteals, adductor stretches

Activity	TO	Land	Condition	Surface	Reps	Speed	Effort
Dual limb							
Run forwards	1	1	From A to B (B = wall)	Outside		Fast	MAX
Vertical jump	2	2	Mark wall with chalk	Outside		Fast	MAX
Run backwards	1	1	From B to A	Outside		Fast	MAX
Vertical jump	2	2	Mark wall with chalk	Outside	60 s	Fast	MAX
Jump down	2	2	90 cm (Black mat)	Soft		Fast	Min
Jump up	2	2	60 cm (if can do)	Soft	5	Fast	MAX
Jump down	2	2	90 cm (Black mat)	Soft		Fast	Min
Jump up	2	2	60 cm (if can do)	Soft		Fast	MAX
Jump down	2	2	60 cm	Soft		Fast	Min
Jump up	2	2	30 cm	Soft		Fast	MAX
Jump down	2	2	30 cm	Soft		Fast	MAX
Vertical jump	2	2	On same level	Soft	5	Fast	MAX
Right limb							
Hop down	1	1	60 cm (Black mat)	Soft		Fast	Min
Hop up	1	1	30 cm (if can do)	Soft		Fast	MAX
Hop down	1	1	30 cm	Soft		Fast	Min
Hop up	1	1	10 cm	Soft		Fast	MAX
Hop down	1	1	10 cm	Soft		Fast	MAX
Vertical hop	1	1	On same level	Soft	5	Fast	MAX
Vertical hops	1	1	Volleyball blocks	Outside	30 s	Fast	MAX
Knee bend	1	1	Eyes closed	Outside	10	Slow	Min
Vertical hop	1	1	Eyes closed	Outside	5	Slow	MAX
Backward hop	1	1	30 cm + 120° CW/CCW	Outside	6	Fast	MAX
Stride D-forward	1	1	30 cm + R 45° CW	Outside	3	Slow	MAX
Stride D-forward	1	1	30 cm + R 45° CCW	Outside	3	Slow	MAX
Stride D-backward	1	1	30 cm + R 45° CW	Outside	3	Slow	MAX
Stride D backward	1	1	30 cm + R 45° CCW	Outside	3	Slow	MAX
Stride D-forward	1	1	30 cm + L 45° CW	Outside	3	Slow	MAX
Stride D-forward	1	1	30 cm + L 45° CCW	Outside	3	Slow	MAX
Stride D-backward	1	1	30 cm + L 45° CW	Outside	3	Slow	MAX
Stride D-backward	1	1	30 cm + L 45° CCW	Outside	3	Slow	MAX
Left limb							
Hop down	1	1	60 cm (Black mat)	Soft		Fast	Min
Hop up	1	1	30 cm (if can do)	Soft		Fast	MAX
Hop down	1	1	30 cm	Soft		Fast	Min
Hop up	1	1	10 cm	Soft		Fast	MAX
Hop down	1	1	10 cm	Soft		Fast	MAX
Vertical hop	1	1	On same level	Soft	5	Fast	MAX
Vertical hops	1	1	Volleyball blocks	Outside	30 s	Fast	MAX
Knee bend	1	1	Eyes closed	Outside	10	Slow	Min
Vertical hop	1	1	Eyes closed	Outside	5	Slow	MAX
Backward hop	1	1	30 cm + 120° CW/CCW	Outside	6	Fast	MAX

Stride D-forward	1	1	30 cm + R 45° CW	Outside	3	Slow	MAX
Stride D-forward	1	1	30 cm + R 45° CCW	Outside	3	Slow	MAX
Stride D-backward	1	1	30 cm + R 45° CW	Outside	3	Slow	MAX
Stride D-backward	1	1	30 cm + R 45° CCW	Outside	3	Slow	MAX
Stride D-forward	1	1	30 cm + L 45° CW	Outside	3	Slow	MAX
Stride D-forward	1	1	30 cm + L 45° CCW	Outside	3	Slow	MAX
Stride D-backward	1	1	30 cm + L 45° CW	Outside	3	Slow	MAX
Stride D-backward	1	1	30 cm + L 45° CCW	Outside	3	Slow	MAX
Right limb							
Run forwards & leap to mark	1	R	Catch football + land, run on & handball return	Outside	10	Fast	MAX
Run backwards & leap to mark	1	R	Catch football + land, run on & handball return	Outside	10	Fast	MAX
Hop forwards	R	R	On same level x 3	Outside		Fast	MAX
Hop vertical	R	R	On same level	Outside		Fast	MAX
Stride backward	R	L	125° CCW + catch ball	Outside	5	Fast	MAX
Run forwards	1	1	On same level	Outside		Fast	Min
Hop	1	1	Scissor legs + stick	Outside	6	Slow	MAX
Square sequence	1	1	Square figure 8 hops	Outside	30 s	Fast	MAX
Left limb							
Run forwards & leap to mark	1	R	Catch football + land, run on & handball return	Outside	10	Fast	MAX
Run backwards & leap to mark	1	R	Catch football + land, run on & handball return	Outside	10	Fast	MAX
Hop forwards	L	L	On same level x 3	Outside		Fast	MAX
Hop vertical	L	L	On same level	Outside		Fast	MAX
Stride backward	L	R	125° CW + catch ball	Outside	5	Fast	MAX
Run forwards	1	1	On same level	Outside		Fast	Min
Hop	1	1	Scissor legs + stick	Outside	6	Slow	MAX
Square sequence	1	1	Square figure 8 hops	Outside	30 s	Fast	MAX
Dual limb							
Jump down	2	2	90 cm (Black mat)	Soft		Fast	Min
Jump up	2	2	60 cm (if can do)	Soft		Fast	MAX
Jump down	2	2	60 cm	Soft		Fast	Min
Jump up	2	2	30 cm	Soft		Fast	MAX
Jump down	2	2	30 cm	Soft		Fast	MAX
Vertical jump	2	2	On same level	Soft	5	Fast	MAX
Jump forwards	2	2	On same level x 3	Outside		Fast	MAX
Jump vertical	2	2	On same level	Outside		Fast	MAX
Bound backward	2	1	To catch football	Outside	5	Fast	MAX
Square sequence	2	2	Square figure 8 jumps	Outside	60 s	Fast	MAX

NB: Slow = hold for 2 s upon landing; L = left; R = right

B. Cool Down (5 mins)

- Quadriceps, hamstrings, triceps surae, hip flexors, gluteals, adductor stretches

Appendix B
Media / Display / Trade Shows / Presentations

During the tenure of the grant, the Intelligent Knee Sleeve has been featured extensively in the media, including on the following national and international television programs:

- The Today Show (Channel 9)
- TechTV (US TV)
- Totally Wild (Channel 10)
- Health Dimensions (ABC)
- Prime News (Regional)
- A Current Affair (Channel 9)

The Intelligent Knee Sleeve was also exhibited at the following trade shows/museums:

- "Textile Future Show" in Germany
- "i-Wear" show in Germany, France and Spain, two shows funded by Messe Frankfurt Avantex, as an emerging technology
- The PowerHouse Museum in Sydney within the Australian Football League exhibit at the exhibition entitled "Sport: More than Heroes and Legends".

The following presentations have been made on behalf of the Intelligent Knee Sleeve and core technology:

- Munro BJ & Steele JR. Muscular control of the lower limb during landing movements: Do males and females respond differently and does participation in landing training programs play a role? *Australian Conference of Science and Medicine in Sport*. Alice Springs, October 2004 (accepted for presentation).
- Munro BJ & Steele JR. Do athletes modify the neuromuscular control of landing after participating in landing training programs? *Australian Conference of Science and Medicine in Sport*. Alice Springs, October 2004 (accepted for presentation).
- Munro BJ. Wearable textile biofeedback systems: Are they too intelligent for the wearer? *New Generation of Wearable Systems for Health: Towards a Revolution of Citizens' Health and Lifestyle Management?* University of Pisa, Centro Interdipartimentale Di Ricerca "E. Piaggio", Tuscany, Italy, December 12-14, 2003, Invited presentation.
- Wallace GG, Campbell TE, Innis PC, Spinks GM, Too CO, Wang J, Xi B, Zhou D, Steele J & Munro B. Intelligent textiles: Wearable sensors, actuators and energy storage systems. *New Generation of Wearable Systems for Health: Towards a Revolution of Citizens' Health and Lifestyle Management?* University of Pisa, Centro Interdipartimentale Di Ricerca "E. Piaggio", Tuscany, Italy, December 12-14, 2003, Invited presentation.
- Mickle K, Ross SA, Munro BJ & Steele JR. Landing training for ACL prevention: Does it improve functionality? *Australian Conference of Science and Medicine in Sport*, Canberra, Australia, October 25-28, 2003. In: *Journal of Science and Medicine in Sport,* December 2003, 6(4) Supplement: 103.
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