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Title: Changes in muscle activation following balance and technique training and a season of Australian football

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Abstract

Objectives: Determine if balance and technique training (BTT) implemented adjunct to 1,001 male Australian football (AF) players' training influenced the activation/strength of the muscles crossing the knee during pre-planned (PpSS) and unplanned (UnSS) sidestepping. **Design:** Randomized Control Trial. **Methods:** Each AF player participated in either 28 weeks of BTT or 'sham' training (ST). Twenty-eight AF players (BTT, n = 12; ST, n = 16) completed biomechanical testing pre-to-post training. Peak knee moments and directed co-contraction ratios (DCCR) in three degrees of freedom, as well as total muscle activation were calculated during PpSS and UnSS. **Results:** No significant differences in muscle activation/strength were observed between the ST and BTT groups. Following a season of AF, knee extensor (p=0.023) and semimembranosus (p=0.006) muscle activation increased during both PpSS and UnSS. Following a season of AF, total muscle activation was 30% lower and peak valgus knee moments 80% greater (p=0.022) during UnSS when compared with PpSS. **Conclusions:** When implemented in a community level training environment, BTT was not effective in changing the activation of the muscles crossing the knee during sidestepping. Following a season of AF, players are better able to support both frontal and sagittal plane knee moments. When compared to PpSS, AF players may be at increased risk of ACL injury during UnSS in the latter half of an AF season.

Key terms: Muscle; Prophylactic; Injury prevention; Exercise; ACL; Knee

Introduction

In Australia, 52/100,000 people per year rupture their anterior cruciate ligament (ACL)[1], representing the highest injury rates per capita world-wide[2]. Two general biomechanical approaches can be used to reduce an athlete's risk of ACL injury in sport. First, decrease the external forces applied to the knee by changing their technique during a sporting task[2,3,4]. Second, increase the strength and/or activation of the muscles with moment arms capable of supporting the knee when external loading is elevated[2,5,6]. Specifically, increasing a muscles ability to support the knee from externally applied flexion and/or anterior shear forces are thought to be appropriate to reduce an athlete's risk of ACL injury in sport[2,7,8], as these are the loading patterns shown to elevate ACL strain *in-vivo*[9]. With no single muscle crossing the knee is capable providing support in all three degrees of freedom simultaneously; therefore different muscle activation strategies can be used to support the knee and ACL during dynamic sporting tasks. In general, muscle activation strategies capable of countering externally applied flexion, valgus, internal rotation moments and/or shear forces include generalized hamstring/quadriceps co-contraction, superimposed with the elevated activation of muscles with flexion, and/or medial moment arms[2].

Incorporating knee joint kinematic and kinetic data presented previously[10] with measures of lower limb muscle activation, which is presented in this manuscript, there were three purposes of this investigation: 1) determine if balance and technique training (BTT) implemented in a 'real-world' training environment, adjunct to normal Australian football (AF) training influenced the activation/strength of the muscles crossing the knee during pre-planned (PpSS) and unplanned (UnSS) sidestepping. 2) Determine if muscle activation/strength changes over a season of AF and 3) determine if changes in muscle activation were proportional to changes in peak knee moments[10]. The term 'real-world' training is defined as an intervention conducted in a field-based, community level training environment, with instruction given by a trainer/coach blinded to the intended aims and outcome measures of the training intervention.

Methods

These methods are a condensed version of those described previously[10,11]. Additionally, interested readers can obtain a complete copy of the BTT and the 'sham' training (ST) intervention training protocols through the corresponding author. This study was approved by the Human Research Ethics Committees at The University of Western Australia (UWA) and the University of Ballarat.

All AF players provided their informed, written consent prior to participating in their respective training interventions and when applicable, biomechanical testing. As part of a larger group-clustered randomized controlled trial, eight Western Australian Amateur Football League clubs (n=1,001 males) volunteered to participate in either 28 weeks of BTT or ST intervention adjunct to their 2007 or 2008 regular season training.

An independent research assistant was contracted to recruit participants by phone for biomechanical testing. From an alphabetical list of the 1,001 eligible AF players, 58 volunteered for biomechanical testing one week prior to (week -1) through the first seven weeks (week 7) of each clubs 8 week pre-season. Of these 58, 34 AF players were available for post testing in weeks 18 to 25 of the 28 week training intervention, which corresponded to the beginning of the BTT and ST maintenance phases. Both knee loading and usable surface electromyography (sEMG) data were obtained from 28 (48%) participants (BTT, n=12; ST, n=16) (Figure 1). Only one of the 24 AF players that did not return for follow-up biomechanical testing was able to be contacted by phone. The reason this individual did not attend follow-up biomechanical testing was due to injury. As we could not contact the remaining 23 AF players, data associated with why they did not attend the second biomechanical testing session is not available.

Each club trained two times per week and played a match once a week over the 28 week training interventions. Training interventions were conducted as a pre-training warm-up for 20 minutes, twice a week for the first 18 weeks, and then once a week until the end of the 28 week training intervention.

Training sessions were run by two instructors blinded to 1) the aim of the training programs they were overseeing, and 2) the outcome variables analyzed during biomechanical testing. Instructors also recorded player attendance and participation following each training session.

Balance training included single-leg, wobble board, stability disk and Swiss stability ball balance tasks. Each balance exercise became progressively more difficult from week 1 to week 18 with the last 10 weeks of training designed as a maintenance phase. Again, all follow up biomechanical testing started in week 18. During each training session, when appropriate, AF players were verbally instructed to keep their stance foot close to midline, maintain a controlled vertical trunk posture and increase knee flexion during the stance phase of both sidestepping and landing tasks.

The ST group served as the experimental control group. The goal of the ST intervention was to improve each athlete's acceleration during straight-line running tasks, which to our knowledge has not been shown to influence an athlete's peak joint loading or ACL injury rates. Other differences between the ST and BTT groups were that the ST group did not receive technique feedback from their instructors and did not participate in any balance type exercises during training. The difficulty of the exercises used in the ST intervention progressed with difficulty in a similar fashion to the BTT protocol.

Each biomechanical testing session started with an assessment of each AF players' lower limb strength. Assessments included maximum effort isometric hip abduction/adduction torque, isokinetic eccentric knee flexion/extension torque, maximum countermovement jump height as well as a single-leg whole-body balance assessment. See supplementary materials B for a full description of these procedures.

Each AF player completed a random series of pre-planned and unplanned straight run, crossover and sidestep sporting tasks with their self-selected preferred leg[10,12]. Participants completed three successful trials of each sporting task before testing was complete. Three-dimensional full-body kinematics were recorded[3,10]. These data, with a custom lower body kinematic model in Bodybuilder (Vicon Peak, Oxford Metrics Ltd., UK) were used to calculate knee flexion angles and peak knee moments via inverse dynamics during weight acceptance (WA). A full description of the kinematic and kinetic modeling approaches used to calculate relevant knee kinematic and kinetic variables have been described previously[10].

During the running and sidestepping trials, sEMG data was collected using a 16-channel telemetry system (TeleMyo 2400 G2, Noraxon, Scottsdale, Arizona) at 1,500 Hz with a 16 bit A/D card. Input impedance was >100 MΩ and CMR was >100 dB. Using bipolar 30 mm disposable surface electrodes (Cleartrace™ Ag/AgCl, ConMed, Utica, NY), with an inter-electrode distance of 30 mm, eight pairs of electrodes were placed over the muscle bellies of eight muscles crossing the knee as per recommendations from Delagi et al.[13] (tensor fasciae latae (TFL) semimembranosus (SM), biceps femoris (BF), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), medial gastrocnemius (MG) and lateral gastrocnemius (LG)).

Using customized software in MatLab (Matlab 7.8, The Math Works, Inc., Natick, Massachusetts, USA), the sEMG data was processed by first removing any direct current offsets, then band-pass filtered with a 4th order Butterworth digital filter between 30 and 500 Hz. The signal was then full-wave rectified and linear enveloped by low-pass filtering with a zero-lag 4th order Butterworth at 6 Hz[7]. Following linear enveloping, peak muscle activation from each muscle (n=8) recorded during pre-planned running (PpRun) was used to normalize each muscle's sEMG signal to 100% activation.

Muscle activation patterns were assessed using mean total muscle activation and directed co-contraction ratios (DCCR) during the pre-contact (PC) and WA phases of the running and sidestepping trials[14]. During the running and sidestepping trials, WA was defined as the period from initial foot contact to the first trough in the vertical GRF vector, while PC was defined as the period 50 ms prior to WA[7]. Mean total muscle activation was calculated by taking the sum of the normalized activation of all muscles crossing the knee. The mean total muscle activation of the hamstring muscles were also calculated and denoted Hamstrings-TMA. The DCCR were calculated for flexion/extension muscle groups, medial/lateral muscle groups and the semimembranosus/biceps femoris (SM/BF). Muscles were grouped according to their ability to produce moments in flexion/extension, varus/valgus and internal/external rotation knee degrees of freedom (See supplementary material A). A DCCR is a ratio between 1 and -1, providing directionality between agonist muscles (flexor and/or medial moment arms) and antagonist muscles (extensor and/or lateral moment arms). A DCCR > 0 would indicate co-contraction is directed towards muscles with flexion and/or medial moment arms, while a DCCR < 0 is directed towards muscles with extension and/or lateral moment arms. A DCCR = 0 indicates equal activation of agonist and antagonist muscle groups.

Muscle activation variables calculated were mean total muscle activation, mean Hamstring-TMA, mean flexion/extension DCCR, mean medial/lateral DCCR and mean SM/BF DCCR. Mean knee flexion (deg), knee flexion RoM (deg), as well as mean peak external knee flexion, valgus and internal rotation moments ($Nm \cdot kg^{-1} \cdot m^{-1}$) were calculated during WA[10].

Only AF players from both biomechanical testing sessions were included for analysis. All variables were assessed using a linear mixed model in SPSS 17.0.1 (SPSS Inc, IBM Headquarters, Chicago, Illinois) (α=0.05). Factors used were time (testing session 1 or 2), training intervention (BTT or ST), running task (PpRun, PpSS or UnSS) and phase (PC or WA). For the analysis of relevant kinematic and kinetic variables, the only phase analyzed was WA[10]. The number of training sessions each AF player participated in between testing sessions was used as a covariate. An adjusted Sidak *post hoc* analysis was used to assess significant main effects and interactions. A Cohen's *d* was used to estimate effect sizes between the BTT and ST groups for all non-significant (α > 0.05) muscle activation variables.

Results

Significant differences in total muscle activation, flexion/extension DCCR and medial/lateral DCCR were observed between the PC and WA phase for all running tasks (p<0.01) (Table 1). Conversely, no differences in Hamstring-TMA or SM/BF DCCR were observed between PC and WA phases for all running tasks, so data were collapsed into one phase for analyses (Table 2).

Total muscle activation was significantly elevated during WA when compared with PC ($p<0.001$) and significantly increased from testing sessions 1 to 2 ($p=0.001$) for all running tasks, within both phases (Table 1). An interaction between running task and training intervention was observed for total muscle activation ($p=0.022$). *Post hoc* analysis showed that total muscle activation during sidestepping tasks were significantly elevated relative to PpRun in both the ST and BTT groups. Total muscle activation was elevated during PpSS relative to UnSS in both training groups, but significance was only attained in the BTT group ($p=0.008$).

An interaction between phase and running task was observed for flexion/extension DCCR ($p=0.016$) (Table 2). *Post hoc* analysis showed flexion/extension DCCR was directed towards muscle with flexion moment arms during PC and extension moment arms during WA for all running tasks. During PC, the flexion/extension DCCR was further directed towards flexion during PpRun when compared with the sidestepping tasks. Furthermore, the flexion/extension DCCR were more directed towards flexion during PpSS when compared with UnSS. During WA, flexion/extension DCCR was more directed towards extension during sidestepping tasks when compared with PpRun. No differences were observed between PpSS and UnSS. Flexion/extension DCCR across both phases and all running tasks became directed more towards muscles with extension moment arms from testing session 1 to 2 ($p=0.023$); meaning the relative activation of the quadriceps and TFL increased over time during both PC and WA.

During testing session 1, SM/BF DCCR was directed laterally towards the BF, for all running tasks. Between testing session 1 and 2 SM/BF DCCR significantly changed ($p=0.006$) and co-contraction increased (SM/BF DCCR=0), meaning the relative activation of the SM increased for all running tasks. No significant differences in SM/BF DCCR were observed between training groups or running tasks (Table 2).

The mean absolute A Cohen's *d* for DCCR variables in the PC and WA phases were 0.18 ± 0.13 (min *d* = 0.01, max *d* = 0.48) and 0.15 ± 0.16 (min *d* = 0.01, max *d* = 0.67) respectively. The mean absolute Cohen's *d* for Hamstring-TMA in the PC and WA phases were 0.22 ± 0.21 (min *d* = 0.01, max *d* = 0.57) and 0.34 ± 0.21 (min *d* = 0.08, max *d* = 0.62) respectively.

In general, no statistical differences in peak isometric hip abduction/adduction torque, isokinetic eccentric knee flexion/extension torque, countermovement jump height nor single-leg whole-body balance score was observed between the ST and BTT and over a season of AF (See Supplementary materials B). The ST training group displayed a 29% increase in preferred sidestepping leg peak isometric hip abduction torque between testing sessions 1 (133±29.2 Nm) and 2 (172±58.8 Nm) (p=0.016).

Discussion

The major finding of this study was that BTT implemented adjunct to AF training did not change the activation patterns or strength of the muscles crossing the knee during either PpSS or UnSS. However, following a season of AF, total muscle activation increased, with minimal changes in muscle strength. Additionally, DCCR were directed towards muscles with extensor moment arms and the SM during both PpSS and UnSS. When analyzing changes in muscle activation/strength in conjunction with changes in peak knee moments[10]; following the playing season, results suggest that the muscles crossing the knee may be better suited to protect the knee and ACL from external knee loading during PpSS when compared with UnSS.

During the second biomechanical testing session, mean PC total muscle activation and quadriceps muscle activation were both significantly elevated during PpSS and UnSS. Sidestepping kinematic data presented previously[10] shows that during WA, mean knee flexion angles during sidestepping were approximately 30º, and knee flexion range of motion increases by 33-35º. Therefore, during WA, the quadriceps would be contracting eccentrically past 20º of knee flexion. Previous research has shown that during the simulated impact phase of landing, elevated eccentric quadriceps force was capable of decreasing ACL strain by increasing joint stiffness and the production of a posteriorly directed joint reaction force beyond 20°of knee flexion[15]. Experimental studies have also shown that the quadriceps are capable of supporting the knee against both varus and valgus knee moments[16,17]. Following a season of AF, increases in total muscle activation and PC quadriceps muscle activation likely served to mitigate athlete's risk of ACL injury during both UnSS and PpSS [2,16].

After as season of AF, the activation of the SM relative to the BF increased during both PpSS and UnSS. The S/M DCCR calculated from data presented previously support these findings[18] (See supplementary material C). Adding to previous literature, results suggest that a season of AF alone is capable of elevating SM activation and reducing ACL injury risk (protecting the knee against external valgus knee moments).

Pre-to-post biomechanical testing, total muscle activation was lower during UnSS when compared with PpSS even in the presence of significantly elevated valgus knee moments[10]. The relative differences in PC total muscle activation between UnSS and PpSS was equivalent (ST 6%, BTT -12%), while valgus knee moments during UnSS were 30% greater than during PpSS[10]. In testing session 2, the relative difference in total muscle activation between UnSS and PpSS remained the same (ST -3%, BTT -10%), while the relative difference in valgus knee moments increased to approximately 80% (0.15 $Nm \cdot kg^{-1} \cdot m^{-1}$)[10]. When muscle activation and knee loading are analyzed together, it is apparent the muscles crossing the knee are less capable of supporting the knee from valgus knee moments during UnSS when compared to PpSS in the latter half of an AF season.

As stated previously[10], the major limitations of this study were low initial participant recruitment numbers, participant retention pre-to-post biomechanical testing (48%), as well as low attendance to the training interventions (BTT = 45±22%; ST = 51±33%)[10]. These are obvious factors limiting the probability of observing positive muscle activation changes following BTT. A recent systematic review of all lower limb injury prevention training interventions has shown that athlete adherence and compliance to a given prophylactic training protocol is an important factor associated with its success (reduce injury rates and/or injury risk)[19]. Though no positive training related muscle activation/strength changes were seen, significant within season changes were observed. Interestingly, these within season changes were similar to findings reported by previous research[18], suggesting there was adequate power to observe changes in muscle activation with the methods used in this study.

Prior to and during the implementation of the training intervention, participant/trainer motivation and attitudes toward the BTT were not recorded. We feel these factors may have contributed to the low levels of athlete attendance/compliance to the training program as well as the high levels of participant drop-out pre-to-post biomechanical testing. Prior to, during and following a prophylactic training intervention, we recommend psycho-social variables are measured[20]. We believe this will provide the literature with a more comprehensive understanding of how focal individuals' perceptions of their injury prevention program may shape their involvement and attainment of desired outcomes, as well as how focal individuals respond to the activities and delivery methods utilised within the program. Guided by principles outlined within the self-determination theory[21], athletes and/or coaches should be informed of the intended benefits of a prophylactic training program[22,23] and provided with choice regarding the completion of core program activities (i.e. tailor the program in a manner that suits them). These recommendations are intended to facilitate adaptive motivational responses among program participants, thereby reducing non-compliance and/or absenteeism, subsequently promoting the prophylactic benefits of the training intervention.

It is apparent that much work is needed before prophylactic training programs like BTT are effectively translated in 'real-world' community level training environments. We hope the experimental methods and prophylactic training protocol presented in this and previous manuscripts[10,11] are used as a framework to help guide and advance future research focused on reducing an athlete's risk of ACL injury and in turn injury rates in sport.

Conclusions

When implemented in 'real-world' training environments, BTT adjunct to normal AF training was not effective in changing the activation of the muscles crossing the knee during PpSS or UnSS. Following a season of AF, knee extensor and SM muscle activation increased and are better able to support frontal and sagittal plane knee moments during PpSS and UnSS. Elevated valgus knee moments combined with relatively low total muscle activation during UnSS suggests an AF player may be at increased risk of ACL injury during UnSS when compared with PpSS in the latter half of an AF season.

Practical Implications:

- Both planned and unplanned sports tasks should be used in the assessment of ACL injury prevention training programs and in the assessment of an athlete's injury risk.
- When analyzing changes in muscle activation in conjunction with changes in peak knee loading, the clinical interpretation of results can change. When possible, changes in muscle activation and knee loading should be assessed together.
- Prior to and/or during the development and implementation of a prophylactic training protocol, athlete/coach perceptions, attitudes and beliefs towards the protocol should be considered.

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Table 1: Total muscle activation and directed co-contraction ratios (DCCR) of the muscles crossing the knee with flexion/extension and medial/lateral moment arms. Data is presented for testing sessions 1 and 2, during both the pre-contact and weight acceptance phases of running and sidestepping. Sham training (ST) and balance and technique training groups (BTT) were pooled together unless an interaction was observed. DCCR > 0 co-contraction is directed towards muscles with flexion and/or medial moment arms. DCCR < 0 co-contraction is directed towards muscles with extension and/or lateral moment arms. DCCR $= 0$ maximal co-contraction.

Phase: Pre-contact		**TMA**		**F/E DCCR**	**M/L DCCR**
		ST	**BTT**		
Testing Session 1	**PpRun**	1.80 ± 0.43 [†,a]	1.95 ± 0.38 [†,a]	0.62 ± 0.15 [†,a]	0.08 ± 0.16 [a]
	PpSS	2.56 ± 0.48 [†,b]	2.87 ± 0.67 [†,b]	0.38 ± 0.24 [†,b]	-0.03 ± 0.19 [b]
	UnSS	2.71 ± 0.94 [†,b]	2.56 ± 0.81 [†,c]	0.17 ± 0.39 [†,c]	-0.09 ± 0.27 [b]
Testing Session 2	**PpRun**	2.01 ± 0.43 [†,a]	2.36 ± 0.61 [†,a]	0.55 ± 0.21 [†,a]	0.14 ± 0.15 [a]
	PpSS	3.18 ± 0.93 [†,b]	3.30 ± 0.70 [†,b]	0.22 ± 0.33 [†,b]	-0.06 ± 0.25 [b]
	UnSS	3.10 ± 1.23 [†,b]	3.01 ± 0.79 [†,c]	0.11 ± 0.30 [†,c]	-0.10 ± 0.22 [b]
Phase: Weight Acceptance		**TMA**		**F/E DCCR**	**M/L DCCR**
		ST	**BTT**		
Testing Session 1	**PpRun**	2.61 ± 0.42 [†,a]	2.84 ± 0.42 [†,a]	-0.03 ± 0.27 [†,a]	0.02 ± 0.17 [a]
	PpSS	3.68 ± 0.58 [†,b]	3.82 ± 0.86 [†,b]	-0.27 ± 0.26 [†,b]	-0.08 ± 0.20 [b]
	UnSS	3.69 ± 1.01 [†,b]	3.46 ± 0.68 [†,c]	-0.29 ± 0.23 [†,b]	-0.08 ± 0.20 [b]
Testing Session 2	**PpRun**	2.77 ± 0.61 [†,a]	3.27 ± 0.75 [†,a]	-0.03 ± 0.24 [†,a]	0.04 ± 0.17 [a]
	PpSS	4.39 ± 0.94 [†,b]	4.29 ± 0.74 [†,b]	-0.38 ± 0.19 [†,b]	-0.16 ± 0.23 [b]
	UnSS	4.09 ± 1.22 [†,b]	3.78 ± 0.71 [†,c]	-0.39 ± 0.23 [†,b]	-0.11 ± 0.27 [b]

† indicates significant difference over time ($p < 0.05$) ($n = 28$).
a,b,c indicates significant Sidak adjusted post hoc difference between independent variables ($p < 0.05$) ($n = 28$).
If two independent variables posses the same letter they are not significantly different from each other.

Table 2: Hamstring-total muscle activation and DCCR of the semimembranosus/biceps femoris (SM/BF) muscles. Data is presented for testing sessions 1 and 2, however the ST and BTT groups as well as the data during the pre-contact and weight acceptance phases of running and sidestepping were pooled.

Phase: Pre-Contact & Weight Acceptance		**Hamstrings-TMA**	**SM/BF DCCR**
Testing Session 1	**PpRun**	0.94 ± 0.33	-0.16 ± 0.24 †
	PpSS	1.11 ± 0.42	-0.14 ± 0.28 †
	UnSS	0.90 ± 0.36	-0.11 ± 0.32 †
Testing Session 2	**PpRun**	1.01 ± 0.34	0.00 ± 0.26 †
	PpSS	1.07 ± 0.38	0.00 ± 0.31 †
	UnSS	0.91 ± 0.33	0.01 ± 0.34 †

† indicates significant difference over time ($p < 0.05$) ($n = 28$).

Figure Caption

Figure 1: Experimental data flow of training intervention and biomechanical testing sessions 1 and 2. BTT and ST number were only reported in testing session two as the biomechanists conducting the data collections were blinded to the training intervention codes of each participant until the statistics phase of the analysis. Mean ± standard deviation age, body mass and height were reported for participants who completed both testing session 1 and 2.

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