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The Effects of a New ACL-Injury Prevention Device on Knee Kinematics and Hamstring and Quadriceps Co-Contraction:

A Pilot Study

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Abstract

Background: The incidence of anterior cruciate ligament (ACL) –injury is 3-5 times greater in female athletes compared to male athletes. This may be partially attributed to lower levels of hamstring-quadriceps co-contraction in females with subsequent knee kinematics that increases risk of ACL-injury. Finding training methods that improves co-contraction and increases knee stability is important.

Objectives: To evaluate the effects of a new device on hamstring-quadriceps co-contraction and to investigate if training with the device can alter knee kinematics in female athletes.

Study design: Controlled experimental study design with repeated measures.

Method: Twenty soccer and floor ball athletes were measured with electromyography (EMG) for hamstring-quadriceps co-contraction while performing squats with and without the device. Thirteen athletes also underwent three-dimensional kinematic analyses, measuring knee abduction angles (at initial ground contact and peak angle) during a drop jump, before and after a six week intervention period with the device. Friedman's test and Wilcoxon signed rank test was used to assess differences and effect sizes (ES) were calculated.

Results: Co-contraction was consistently larger on the device (medial side: $p<0.001$, ES=0.88; lateral side: $p<0.001$, ES=0.80) and the ratio of medial-to-lateral co-contraction increased ($p=0.001$, ES=0.79). In the kinematic analysis low adherence rates amongst our subjects meant that the effects of the device on kinematics could not be measured.

Conclusion: Performing squats with the new training device stimulates increased hamstring-quadriceps co-contraction and increases the ratio of medial-to-lateral co-contraction. The effects of the device on knee kinematics have yet to be determined.

Abstrakt

Bakgrund: Frekvensen av korsbands (ACL) –skador är 3-5 gånger högre hos kvinnliga idrottare jämfört med manliga. Detta kan delvis härledas till en nedsatt hamstring-quadriceps co-kontraktion hos kvinnor med påföljden att rörelsemönster som ökar risken för ACL-skador blir mer vanliga. Att utveckla träningsmetoder som kan förbättra hamstring-quadriceps co-kontraktionen och öka knästabiliteten hos kvinnliga idrottare är viktigt.

Syfte: Att utvärdera effekterna av ett nytt träningsredskap på hamstring-quadriceps co-kontraktion samt undersöka om träning med redskapet kan förändra rörelsemöster i de lägre extremiteterna hos kvinnliga idrottare.

Studie design: Kontrollerad experimentell studie med upprepade mätningar.

Metod: Tjugo kvinnliga fotbolls- och innebandy spelare utförde knäböjningar med och utan redskapet samtidigt som hamstring-quadriceps co-kontraktion mättes med elektromyografi (EMG). På tretton idrottare analyserades även knä abduktions vinklar (vid fotnedsättning samt max-vinkel) vid nedhopp med hjälp av ett 3D system. Detta skedde före och efter en sex veckors interventionsperiod med redskapet. Friedman's test samt Wilcoxon signed rank test användes i den statistiska analysen och effekt storlek (ES) beräknades för skillnader.

Resultat: Co-kontraktionen var konsekvent högre med redskapet (mediala sidan: $p<0.001$, ES=0.88; laterala sidan: $p<0.001$, ES=0.80) samt även ration av medial-till-lateral co-kontraktion ($p=0.001$, ES=0.79). Låg åtföljnad till interventionen bland våra försökspersoner innebar att vi inte kunde mäta redskapets träningseffekt på rörelsemönster.

Slutsats: Att träna med redskapet stimulerar till ökad hamstring-quadriceps co-kontraktion samt ökar ration av medial-till-lateral co-kontraktion. Träningsredskapets faktiska påverkan på rörelsemönster har ännu inte fastställts.

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1. Introduction

Anterior cruciate ligament (ACL) -injury is arguably the most common serious knee injury associated with sports participation. Approximately 5000 individuals suffer an ACL-injury in Sweden every year (Frobell, Lohmander et al. 2007). The majority of ACL-injuries occur in sports during noncontact situations such as landing from jumps and cutting activities (Boden, Dean et al. 2000, Olsen, Myklebust et al. 2004). Surgeries and rehabilitation associated with these injuries imply huge financial costs for society each year and it is therefore important to develop effective prevention strategies. Females are particularly exposed and run a 3-5 times greater risk of injury compared to males (Lohmander, Englund et al. 2007). This has partly been attributed to lower levels of hamstring quadriceps co-contraction in female athletes with subsequent negative effects on knee kinematics (Hewett, Myer et al. 2006). Existing exercises for increased co-contraction and stability does not fully meet the demands that are encountered in sports and may therefore not promote optimal co-contraction patterns. We have, based on a typical ACL-injury mechanism, attempted to create an exercise that meet the demands high risk sports activities put on knee stability. This exercise is intended to be used as a complement to training methods that are already in practice.

1.1 Knee kinematics & ACL-injury

Athletic activities like cutting and landing from jumps expose the knee to high flexion torques that must be opposed by the quadriceps musculature (Besier, Lloyd et al. 2001, Withrow, Huston et al. 2006). Quadriceps inserts on the proximal-anterior part of tibia and isolated contraction of the muscle will cause anterior translation of tibia in relation to femur, putting strain on the ACL and possibly rupture the ligament (Renström, Arms et al. 1986, DeMorat, Weinhold et al. 2004, Withrow, Huston et al. 2006). In addition, landing and cutting manoeuvres produce abduction, adduction and rotational torques about the hip and knee (Besier, Lloyd et al. 2001). Without an opposing force to these torques the loaded leg(s) will be forced into the valgus position with the femur adducted and internally rotated, the tibia externally rotated and the knee abducted further increasing strain on the ACL (Markolf, Burchfield et al. 1995). Ireland (2002) has labelled this “the position of no return” because it places the stabilizing muscles of the knee in a mechanical disadvantage disabling them from re-establishing a sound posture. Several studies (Ford, Myer et al. 2003, Zeller, McCrory et al. 2003, Olsen, Myklebust et al. 2004, Hewett, Myer et al. 2005) have linked the “position of no return” to an increased risk of knee injury. Female athletes exhibit increased knee valgus movement patterns during landing and cutting activities compared to male athletes (Chappell, Yu et al. 2002, Ford, Myer et al. 2003, Zeller, McCrory et al. 2003, Olsen, Myklebust et al. 2004). Hewett et al. (2003) demonstrated that the knee abduction angles (as indicators of knee valgus) at peak and initial ground contact during a drop jump can predict non-contact ACL-injury in female athletes and concluded that prevention of dynamic knee valgus is likely to decrease ACL-injury rate in females (Hewett, Myer et al. 2005). Factors that contribute to knee valgus movement patterns and thus increased knee abduction angles in female athletes may be anatomical, hormonal or neuromuscular(Hewett, Myer et al. 2006). However, several studies (Hewett, Lindenfeld et al. 1999, Hewett, Myer et al. 2005, Myer, Ford et al. 2005) have emphasized the importance of neuromuscular factors, partly because such factors can be influenced through training. The importance of neuromuscular factors is also confirmed by the fact that studies attempting to improve neuromuscular control have been successful in decreasing ACL-injury rates in females (Hewett, Lindenfeld et al. 1999, Mandelbaum, Silvers et al. 2005).

1.2 Hamstring-Quadriceps Co-contraction

One of the primary neuromuscular strategies for knee stabilization is through simultaneous contraction of the quadriceps- and hamstring musculature. At knee flexion angles greater than 15 to 30 degrees, co-contraction of the hamstrings during quadriceps dominant activities is believed to counteract the anterior displacement of tibia, thus protecting the ACL (Draganich, Jaeger et al. 1989, Hirokawa, Solomonow et al. 1991, More, Karras et al. 1993, MacWilliams, Wilson et al. 1999). Quadriceps and hamstring co-contraction also plays a major role in protecting against abduction and adduction torques by compressing the joint and increasing joint stiffness, thus reducing knee laxity in all planes (Goldfuss, Morehouse et al. 1973, Louie and Mote Jr 1987).

Sex differences in hamstring-quadriceps co-contraction levels have been identified. Female athletes demonstrate higher levels of quadriceps activation and lower levels of hamstring activation during running, jumping and cutting activities compared to males and subsequently lower levels of hamstring-quadriceps co-contraction (Malinzak, Colby et al. 2001, Zazulak, Ponce et al. 2005). Furthermore, females have been found to exhibit imbalanced (lower) medial-to-lateral- hamstring activity (Rozzi, Lephart et al. 1999), quadriceps activity (Myer, Ford et al. 2005) and co-contraction (Palmieri-Smith, McLean et al. 2009) compared to males. Disproportionately greater recruitment of the muscles on the lateral side of the knee will compress the joint laterally while opening it medially and may, at least partly, explain why female knees are less resistant to valgus loading (Rozzi, Lephart et al. 1999, Sell, Ferris et al. 2007, Palmieri-Smith, McLean et al. 2009).

Most training interventions that deal with knee stability in female athletes include exercises for increased hamstring and quadriceps co-contraction. Typical examples are closed-kinetic chain movements performed on unstable surfaces which challenge knee stability and thus stimulate increased hamstring-quadriceps co-contraction (Irrgang and Neri 2000). A few kinematic intervention studies that have incorporated this type of exercises have successfully altered knee kinematics in female athletes during jumping tasks (Lephart, Abt et al. 2005, Myer, Ford et al. 2006). However, because all of these studies have employed multiple training methods simultaneously it is difficult to determine if and how the balance exercises contributed to the results. Injury prevention studies that have used similar exercises as exclusive components have not been successful in significantly decreasing knee- and ACL-injury rate in female athletes (Wedderkopp, Kaltoft et al. 1999, Söderman, Werner et al. 2000). One apparent disadvantage with the balance exercises is that they do not resemble conditions in sports (since sports are not played on unstable surfaces). Balance exercises offer random perturbations that have proven effective in decreasing muscle reflex latencies (Ihara and Nakayama 1986, Beard, Dodd et al. 1994) and improving balance but do perhaps not promote co-contraction patterns that are optimal for sports participation. Activities such as jumping and cutting specifically challenge knee valgus stability, i.e. external rotation of the foot and abduction loads towards the knee, which is opposed mainly by medial hamstring and quadriceps co-contraction (Lloyd and Buchanan 2001). Thus, exercises that selectively activate the medial muscles of the knee should be included in ACL-injury prevention training (Lloyd 2001) and perhaps especially in the training of female athletes because of their decreased medial-to-lateral co-contraction ratio. To our knowledge no exercises exist that are designed to selectively activate the medial muscles of the knee. More importantly, we know of no exercises that accomplish increased medial muscle activation by exposing the foot to transverse rotational force, an important kinematic contributor to ACL-injury. We attempted to create an exercise that includes the aforementioned qualities by constructing a special squatting device. The squat is a closed-kinetic chain movement with simultaneous hip- and knee flexion, similar in many ways to landing and cutting activities. Further, the bilateral squat requires less balance than unilateral leg exercises which makes it safe and easy to perform even by individuals with poor lower extremity control.

1.3 Objectives

The overall objectives of this study were to evaluate the effects of the new device on hamstring-quadriceps co-contraction and to investigate if training with the device could alter knee kinematics in female athletes.

The specific aims were:

(i) To evaluate the hamstring-quadriceps co-contraction on both the medial and lateral side of the knee during squats with and without the new device.

(ii) To compare medial-to-lateral co-contraction ratios with and without the device.

(iii) To analyse knee abduction angles (peak angles and at initial ground contact) during a drop jump landing before and after a 6-week intervention period with the device.

2. Materials & Methods

2.1 Subjects

A controlled experimental study design with repeated measures was used for this investigation and the subjects thus served as their own controls. Forty-five female athletes from two local sports teams - one soccer team and one floor ball team - were visually inspected during drop jumps for dynamic knee abduction during any part of the landing phase. Knee abduction was defined as the distal femur toward and the distal tibia away from the midline of the body. Only subjects with marked knee abduction movement were to be selected as we believed that there was a greater chance of improvement in such subjects. Athletes who were positively assessed by both of the two test leaders were asked to participate in the study (n=22). Exclusion criteria were present or past knee injuries.

2.2 The device

The device (figure 1) consists of two circular platforms (Ø 0.32 m, height 0.065 m) that are placed on the floor and on which the user stands to perform squats. Each platform is comprised of two boards – a bottom board with a centre hole containing a ball bearing and a top board with a centre axis that is inserted into the ball bearing of the bottom board. This allows transverse rotation of the top half of the device in relation to the bottom half. Elastic bands interconnect the boards and offer resistance against internal rotation. Support brackets for the feet are mounted on top of each platform. To perform squats the platforms should be positioned approximately one shoulder width apart on the floor with the support brackets pointing slightly outwards. The user then places the outside of the feet against the brackets with the heels in line with the rear edges of the platforms (figure 1 b). By pushing the outside of the heels against the brackets, the top boards (and the feet) will rotate internally (since the heels are positioned outside the centre of rotation)(figure 1 c). When the feet are pointing straight forward or slightly out to the sides the subject is in position to squat. The subject must actively work to maintain the position of the boards throughout the entire squatting motion or the boards together with the feet will rotate externally and the knees will buckle inwards assuming the valgus position. The resistance of the exercise can be varied by rotating the entire device on the floor. The more outwards the support brackets are pointing the greater force will be required to bring the top boards to the neutral squatting position.

Figure 1. (a) Side view of the device, Ø 0.32 m, height 0.065 m. (b) Starting position with the feet against the supports, (c) By pushing the feet apart the top plates will rotate internally. The subject is in position to squat

2.3 Procedures

All subjects participated in three laboratory sessions interspersed six weeks apart. All sessions assessed knee kinematics during drop jumps and the first session included electromyography (EMG) -tests to analyze hamstring-quadriceps co-contraction while squatting with and without the device. The first laboratory session was followed by a six week control period during which the subjects carried on with their normal training. This period was included to ascertain that no confounding variables that might affect knee kinematics were present. After six weeks a new assessment was conducted and the training intervention with the device was initiated. Another six weeks later the intervention period was terminated and a final assessment of knee kinematics was conducted.

2.4 EMG-testing

For EMG measurements the Biomonitor ME6000 8-channels system (Mega Electronics Ltd., Kuopio, Finland) was being used. The amplifiers combined permitted gain was 100-1000 with a bandwidth of 8-500 Hz. The common mode rejection was 110 dB. Data was collected at a sampling frequency of 1000Hz. Muscle activity was recorded from the biceps femoris (BF), the semitendinosus (ST), the vastus lateralis (VL) and the vastus medialis (VM). The skin was cleaned with ethanol before two circular (ø 10 mm) ambu blue sensor surface electrodes (Ambu A/S. Ballerup, Denmark) were attached over the muscle bellies of each muscle, in line with the direction of the fibres and with a 20 mm inter-electrode distance. A third reference electrode was attached perpendicular to the recording electrodes to enable differential amplification. Precise attachment sites for recording electrodes on the respective muscles were as follow: The BF - half the distance from the ischial tuberosity to the lateral epicondyle of the tibia; the ST - half the distance from the ischial tuberosity to the medial epicondyle of the tibia; the VL - at 2/3 of the distance from the anterior superior iliac spine (ASIS) to the lateral side of the patella; and the VM - at 80% of the distance from the ASIS and the joint space in front of the anterior border of the medial ligament (Hermens, Freriks et al. 2000).

SEMG data during two five second maximum voluntary isometric contractions (MVIC) against manual resistance was recorded from each of the muscles according to recommendations by Perotto et al. (1994):

- VL & VM - From a supine position with the right hip and knee passively flexed 45°, participants attempted to extend the right knee against manual resistance from the researcher.
- BF & ST - From a standing position, supporting themselves against a wall and with the right knee actively flexed 90°, participants attempted to flex the knee against manual resistance from the researcher.

After the MVIC’s the squatting trials began, starting with unloaded squats on the floor. Subjects assumed a stance with the feet approximately one shoulder width apart and were instructed to squat down to a depth that coincided with 90 degrees of knee flexion, as measured by the test leader with a set square. Squats were performed in cadence to a metronome set at 60 beats per minute and subjects were instructed to make the eccentric and concentric phases each last two beats. When the subjects were familiar with proper execution testing began. Five separate repetitions were performed. Identical conditions were applied during squats on the device except that the subjects also had to actively prevent the plates from rotating, according to instructions described in the section about the device.

The raw EMG-signal was band pass filtered with a high-pass frequency of 10 Hz and a low-pass frequency of 400 Hz and then Root Mean Squared (RMS) averaged. Data from the squatting trials were normalized to each muscle's MVIC. Muscle co-contraction was calculated in excel using the normalized RMS average of each muscle and the following formula: (SEMG-activity of less active muscle/SEMG-activity of more active muscle) × (SEMG-activity of less active muscle + SEMG-activity of more active muscle). This formula, developed by Rudolph et al. (2001), considers both the relative contribution of each muscle as well as the total magnitude of co-contraction. The ratio of medial-to-lateral co-contraction was calculated in SPSS.

2.5 Three-dimensional (3D) kinematic analysis

Subjects performed drop jumps from a 31 cm box with the feet positioned 35 cm apart. Each subject was instructed to step out from the box and to drop straight down, land with both feet simultaneously and then instantly explode upwards as high as possible. A force plate was used to help determine initial ground contact and peak knee abduction angles during the stance phase of the landing. The same testing protocol has been used by other authors (Hewett, Myer et al. 2005, Joseph, Tiberio et al. 2008, Joseph, Rahl et al. 2011) and show excellent reliability for kinematic data (Joseph, Tiberio et al. 2008). For each subject five trials were recorded of which the first three successful ones were used for analysis. The motion data was captured with six ProReflex cameras at a frame rate of 240 Hz for five seconds and processed by the Qualisys Track Manager software (QUALISYS AB, Gothenburg, Sweden). Retro reflective markers (reflecting infrared light emitted by the cameras) were applied on the subjects according to recommendations by Qualisys. The following anatomical landmarks were used: Sacrum, crista iliaca, ASIS, trochanter major, superior patella, lateral and medial knee joint lines, tibial tuberosity, lateral and medial malleolus, 2nd metatarsale, calcaneus (figure 2).

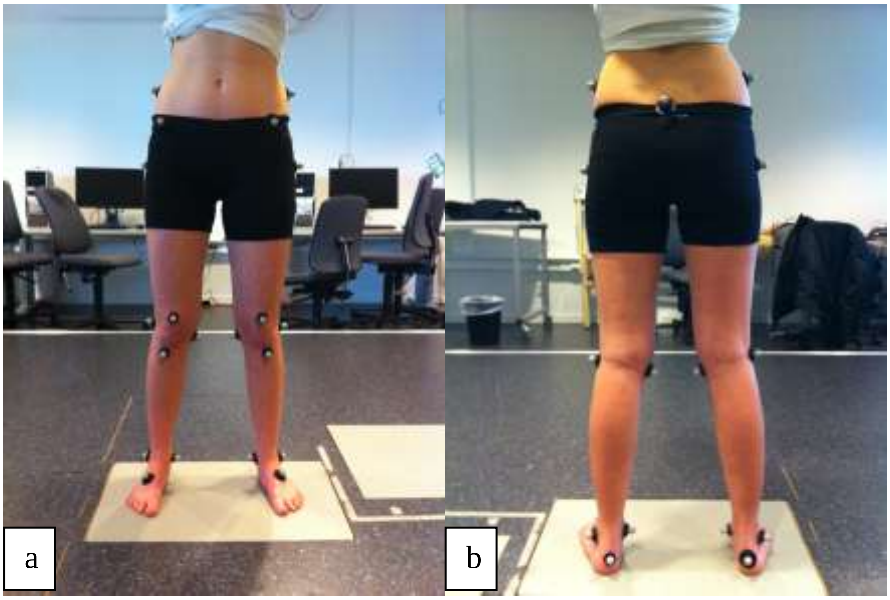

Figure 2. The marker set-up that was used for the 3D motion capture. Front view (a) and rear view (b).

After having calibrated cameras and force plates a static trial of the subject was recorded. Trajectories were manually identified and the file was saved and used to generate an Automatic Identification of Markers (AIM) model that was applied on subsequent motion trials. In trials that resulted in multiple trajectories for the same marker(s) the trajectories were joint together and gap-filled, for gaps not exceeding 30 frames. All motion data was exported to the Visual 3D motion analysis software where it was interpolated and low pass filtered (Butterworth). A skeletal model was then built from one of the subject's 3D-data and tracking markers for each segment was defined. The skeletal model was turned into a generic model file and saved. A pipeline was constructed to compute knee joint angles and the saved model file was integrated into the pipeline for automatic model building. Local coordinates of each body segment were defined at the proximal joint centre. The relative position of the shank to the thigh was used for knee angle computations and a cardan sequence of x-y-z was applied, so that flexion/extension revolved around the x-axis, abduction/adduction around the y-axis and longitudinal rotation around the z-axis. When the local coordinate systems of the thigh and shank were aligned rotation about any axis was zero. Knee abduction angles at initial ground contact (Ab-IC) and peak- abduction (PeakAb) were determined and collected from the right leg (Chappell and Limpisvasti 2008).

2.6 Training routine

Subjects were instructed to train with the device four days a week as part of the warm up routine before their regular soccer or floor ball practice. Each session consisted of squats on the device, executed in four sets of 15 repetitions with one minute rest in between sets (Swanik, Lephart et al.). To instruct the subjects on correct exercise performance we used a routine where we first demonstrated the exercise and then had the subjects practice themselves while we encouraged them on with standardized cues. The coaches at the clubs were educated the same way. It was determined that a minimum of 19 sessions (80%) should be performed by each subject in order for the intervention to have an effect (Pollard, Sigward et al. 2006). To control the training frequency subjects were instructed to check their names on a list after every session.

2.7 Ethical & social considerations

Written informed consent was obtained from all subjects and from the subject's guardian if the subject was a minor. Participation was anonymous and any information related to the subjects' personal identification was disguised and could not be traced to the gathered test data. There were no risks involved with participating in the study.

2.7 Statistical analyses

An assessment of normality revealed that the results were non-parametric. Median and minimum-maximum (min-max) values were calculated for all measured variables. The Wilcoxon signed-rank test was used to assess differences in co-contraction with and without the device. The Friedman test was used to compare knee kinematic values from the three different assessments and in cases where significant differences were found post-hoc analysis with the Wilcoxon signed rank test was performed. Because multiple comparisons of kinematic values were made a Bonferroni adjusted significance level was here taken into account. The original significance level was set to $p=0.05$. Wilcoxon effect sizes were calculated for the differences by dividing the Z score with the square root of n subjects. A small, medium and large size difference is indicated by an effect size of 0.1, 0.2 and 0.5 respectively (Field 2005). SPSS version 18.0 for Windows XP was used in the statistical analysis.

3. Results

Out of 45 examined female athletes 22 qualified for participation. However, two athletes chose not to participate and 20 subjects underwent the first kinematic analysis and the co-contraction analysis (Co-contraction group (Cc), table 1). During the course of the study two athletes suffered knee injuries (1 ACL-injury), two had to be excluded due to errors in the data collection and three chose to terminate their participation before the end of the study (figure 3). Thus, 13 female athletes made it to the last assessment and constituted the kinematics group (KIN) (table 1) on which analysis of knee abduction angles were performed. However, only two of the subjects in KIN reported to have fulfilled the required number of training sessions. Nevertheless, kinematic data and statistical analyses of the whole group are presented in order to give better insight into the intended methodology.

Table 1. Subject data (age, height and weight) for the Co-contraction group (Cc) and the kinematics group (KIN). Median and minimum-maximum (min-max) values are presented.

	Age (min-max)	**Height (min-max)**	**Weight (min-max)**
EMG (n=20)	19 years (15-39 years)	167 cm (159-178 cm)	63 kg (47-70 kg)
KIN (n=13)	18 years (15-39 years)	167 cm (159-178 cm)	66 kg (47-70 kg)

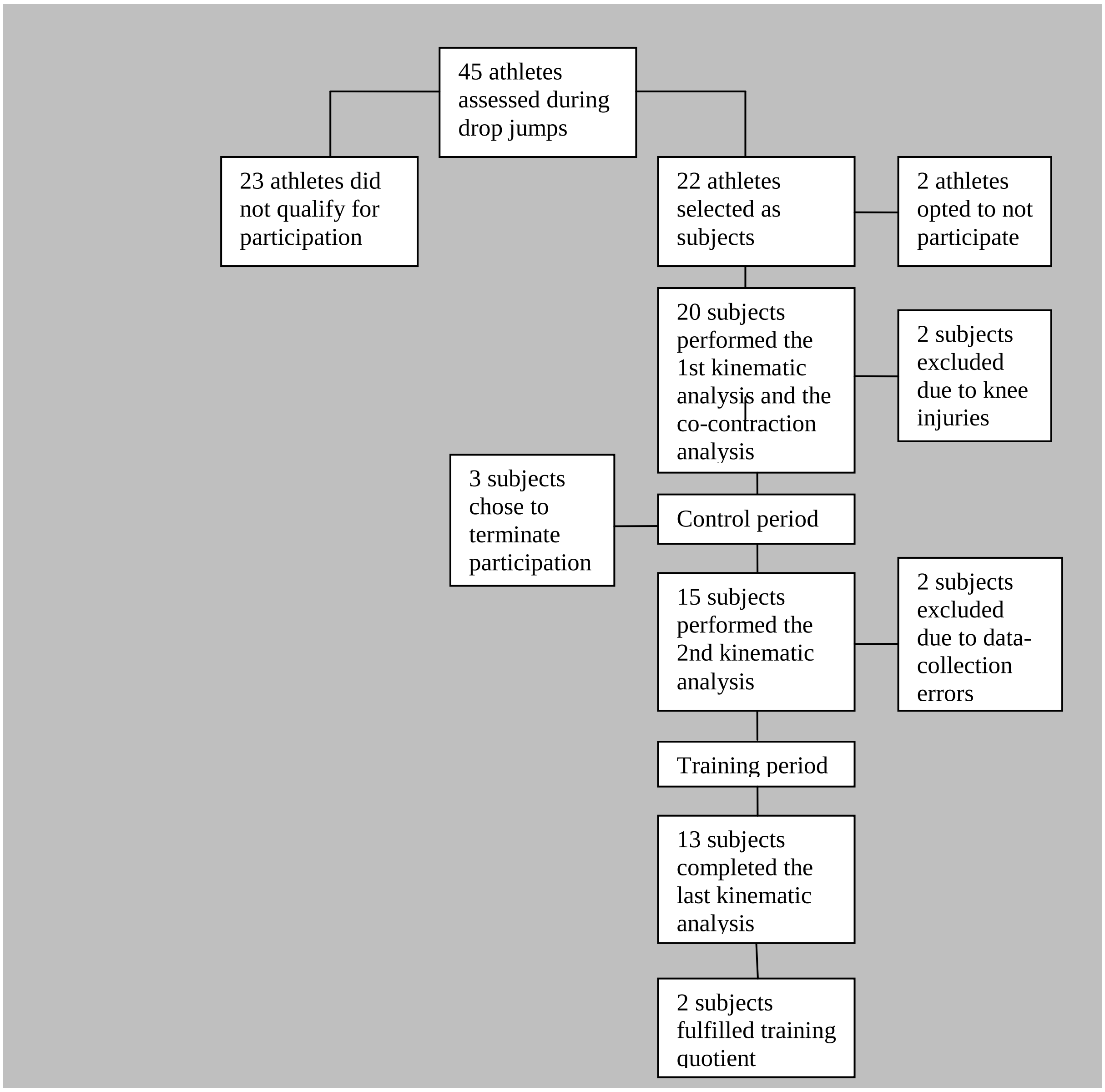

Figure 3. Flow chart showing the participation of subjects over the course of the study.

3.1 Co-contraction

Co-contraction (Cc) -indexes (presented in table 2) were consistently larger when squatting on the device compared to squatting on the floor (ST-VM: $p<0.001$; BF-VL: $p<0.001$). The most pronounced differences were found in ST-VM, with an increase in the median Cc-index from 9.73 (min-max=2.07-20, 83) to 20.92 (min-max=4.39-39.00) yielding an effect size of 0.88. In the BF-VL the differences were smaller, showing an increase in the median Cc-index from 9.36 (min-max=2.13-19.03) to 11.53 (min-max=4.40-29.32) with an effect size of 0.80. Consistent increases were also found in the medial-to-lateral ratio of co-contraction ($p=0.001$) where the median value went from 1.01 (min-max=0.56-1.95) to 1.64 (min-max=0.38-3.14) resulting in an effect size of 0.79 (table 2). The corresponding changes in EMG-activity for the individual muscles are presented in table 2. An increase in activity was seen in the ST (p<0.001, ES=0.86) as well as in the BF (p=0.001, ES=0.77) while there was a decrease in both the VM (p=0.049, ES=0.45) and the VL (p=0.001, ES=0.75) (table 3).

Table 2. Co-contraction index during squats with and without the device. Results are presented in median (m) and minimum-maximum (min-max) values. Statistical differences (Wilcoxon) between the two conditions are presented with p-values and effect size (ES) n=20.

	Without device	**With device**		
Muscles	m (min-max)	m (min-max)	p-values	ES
ST-VM (medial muscles)	9.73 (2.07-20.83)	20.92 (4.39-39.00)	<0.001	0.88
BF-VL (lateral muscles)	9.36 (2.13-19.03)	11.53 (4.40-29.32)	<0.001	0.80
Ratio STVM/BFVL (medial/lateral)	1.01 (0.56-1.95)	1.64 (0.38-3.14)	0.001	0.79

ST-VM=Semitendinosus-Vastus medialis; BF-VL=Biceps femoris-Vastus lateralis

Table 3. Root mean squared (RMS) -averaged and normalized electromyography (EMG) values in median (m) and minimum-maximum (min-max) for the individual muscles during both conditions. Statistical differences (Wilcoxon) are presented with p-values and effect size (ES) (n=20).

	Without device	**With device**		
Muscles	m (min-max)	m (min-max)	p-values	ES
VM (medial)	49.00 (17.00-61.00)	41.00 (16.00-63.00)	0.049	0.45
VL (lateral)	46.00 (29.00-64.00)	43.00 (17.00-59.00)	0.001	0.75
ST (medial)	8.00 (2.00-16.00)	15.00 (4.00-26.00)	<0.001	0.86
BF (lateral)	8.00 (2.00-14.00)	9.00 (4.00-21.00)	0.001	0.77

VM=Vastus medialis; VL=Vastus lateralis; ST=Semitendinosus; BF=Biceps femoris

3.2 Kinematics

Analysis of the kinematic variables revealed a significant difference between the three different test occasions (1: Pre-control, 2: Post-control/pretraining and 3: Post-training) for both knee abduction angles at initial ground contact (Ab-IC) (p=0.005) and peak knee abduction angles (PeakAb) (p=0.001)(table 4). Post-hoc analyses on the variables showed that the differences existed between the Pre-control versus the Post-control/pre-training analysis (Ab-IC: p=0.01, ES=0.7; PeakAb: p=0.002, ES=0.9) and the Pre-control versus the Post-training analysis (Ab-IC: p=0.01, ES=0.7; PeakAb: p=0.003, ES=0.8) (table 5). No significant change in the variables were found between the Post-control/pretraining analysis and the Post-training analysis (Ab-IC: p=0.762, ES=0.08; PeakAb: p=0.752, ES=0.09) (table 5).

Table 4. Kinematic values – knee abduction angles at initial ground contact (Ab-IC) and peak knee abduction angles (PeakAb) - during the three different analyses. Results are presented in median (m) and minimum-maximum (min-max) values. Friedman's test was used to assess statistical differences between the three analyses for both variables. Differences are presented with p-values (n=13).

	PREC	**POSTC/PRET**	**POSTT**	
Kinematics	m (min-max)	m (min-max)	m (min-max)	p-values
Ab-IC	9.00 (5.00-18.00)	7.00 (4.00-13.00)	6.00 (3.00-12.00)	0.005
PeakAb	18.00 (13.00-25.00)	15.00 (7.00-22.00)	15.00 (8.00-22.00)	0.001

PPREC=Precontrol; POSTC/PRET=Postcontrol/pretraining; POSTT=Posttraining

Table 5. Post-hoc analyses. Comparisons were made between analyses, pairwise, using the Wilcoxon signed rank test. Median (m) differences, minimum-maximum (min-max) values, p-values and effect size (ES) are presented. Because multiple (three) comparisons have been made the significance level must be bonferroni adjusted accordingly (p=0.05/3, p=0.02)(n=13).

	PREC			**POSTC/PRET**			**POSTT**		
Kinematics	m (min-max)	p-values	ES	m (min-max)	p-values	ES	m (min-max)	p-values	ES
Ab-IC	1.00(-1.00–10.00)	0.01	0.7	2.00(-2.00–12.00)	.01	0.7	0.00(-2.00–4.00)	0.762	0.08
PeakAb	3.00(0.00-10.00)	0.002	0.9	4.00(-1.00-10.00)	0.003	0.8	5.00(-7.00-7.00)	0.752	0.09

PPREC=Precontrol; POSTC/PRET=Postcontrol/pretraining; POSTT=Posttraining

For both of the two subjects that performed the required number of training sessions there was some decrease in knee abduction kinematics. In one subject PeakAb decreased by 3 degrees while Ab-IC remained unchanged and in the other subject Ab-IC decreased by 2 degrees while PeakAb remained unchanged.

4. Discussion

The EMG-results indicated that squatting with the new device stimulates increased hamstring-quadriceps co-contraction as Cc-index increased for both ST-VM and BF-VL compared to squatting without it. Further, effect sizes of 0.88 and 0.80 indicate that the differences were large. The increased levels of co-contraction were partly due to increased hamstring activity but also to a decreased quadriceps activity. Both hamstring muscles showed greater activity with the device but the largest increases was found in the ST. Muscle activity decreased somewhat for both quadriceps muscles but the decrease was greater in the VL. Consequently the ratio of medial-to-lateral activity increased for both the quadriceps and hamstring muscles resulting in an increased medial-to-lateral co-contraction. Also here were the differences large, as indicated by an effect size of 0.79.

Substantial alterations in ST activity were expected as one of the functions of the ST is to internally rotate tibia or, as in this case, stabilize against the external rotation that was applied to the feet. This effect was also desired as female athletes have demonstrated decreased medial-to-lateral -hamstring, -quadriceps and -co-contraction ratios during athletic activities, which may predispose the knee to dynamic valgus and increase ACL-injury risk (Rozzi, Lephart et al. 1999, Sell, Ferris et al. 2007, Palmieri-Smith, McLean et al. 2009). Stimulating selective activation of the medial muscles of the knee will increase medial-to-lateral co-contraction ratios and make the knees more tolerant to valgus loading (Lloyd and Buchanan 2001). Perhaps less expected was the fact that quadriceps activity decreased. However, reduced quadriceps activity have been noticed in anterior cruciate ligament deficient subjects and suggested to be a strategy to limit the anterior pull of the quadriceps on tibia (Berchuck, Andriacchi et al. 1990). It is possible that the subjects in our study employed a similar strategy as the demand on the joint increased. This seems especially plausible if the hamstring muscle is weak relative to the quadriceps (Aagaard, Simonsen et al. 1998), as has been found to be the case in female subjects. While such a strategy will limit efficiency it may be an acute adaptation to balance the forces around the joint that will diminish as hamstring strength increases and/or the subject becomes more familiar with the movement.

In comparison to previous studies on hamstring quadriceps co-contraction the values in the present study appears to be in the similar range. Shields et al. (2005) measured hamstring and quadriceps activity and co-contraction in male and female athletes during an unloaded single leg squat. While Cc-indexes were not used in this study the RMS EMG-data was presented so that Cc-index could be calculated. This resulted in mean values of 7.18 and

12.36 for the ST-VM and the BF-VL respectively and a medial-to-lateral co-contraction ratio of 0.58, slightly different from the median Cc-index values that our subjects exhibited during the unloaded squat and almost half of the co-contraction ratio. However, back to back comparisons between our median values and the mean values recorded by Shields et al. (2005) may not be appropriate as median values are relatively poor representatives of the non-parametric distribution they stem from. What can be said, at best, is that the values that we recorded were distributed around the values recorded by Shields et al. (2005) and thus appears to be valid measures of co-contraction during an unloaded squat.

With the device we wanted to imitate the demands that sport activities such as jumping has on hamstring-quadriceps co-contraction. In a study (Palmieri-Smith, McLean et al. 2009) on hamstring –quadriceps contraction during drop jumps female athletes demonstrated mean Cc-indexes of 22.91 (SD~ 0.02) and 33.52 (SD~ 0.02) for medial and lateral co-contraction respectively and a medial-to-lateral hamstring-quadriceps co-contraction ratio of 0.68. When our subjects squatted with the device the medial co-contraction values ranged from 4.49-39.00, with a median value of 20.92. Thus, some of the values were similar or higher to those reported by Palmieri et al. while others were much lower. On the lateral side squats with the device produced consistently lower co-contraction values (median: 11.53, min-max: 4.40-29.32) compared to the values presented by Palmieri et al. The medial-to-lateral co-contraction ratios for subjects squatting with the device ranged between 0.38-3.14. Thus, some of our subjects exhibited medial-to-lateral co-contraction ratios that were similar to the ones exhibited by female athletes during drop jumps while others of our subjects exhibited either much higher or much lower ratios. A factor contributing to the widely scattered values may be the fact that resistance was not adjusted to the subjects' individual strength levels. Had a load that produced a certain ratio of medial-to-lateral co-contraction been established for each individual athlete it is likely that the data would have assumed normal distribution. Ideally, a load that has similar demands on hamstring-quadriceps co-contraction as jump landings should be selected. However, since the decreased co-contraction levels and medial-to-lateral co-contraction ratios that females exhibit during jump landings are established risk factors for ACL-injury it seems logical that a load that produces co-contraction values closer to the ones exhibited by males should be the goal. But if this truly is the case or if female athletes should aim for other co-contraction values in order to maintain joint stability during athletic activities is a matter for future research.

The results of the co-contraction analysis in this study show that the device can be used to increase the level of hamstring-quadriceps co-contraction and the medial-to-lateral co-contraction ratio. Nevertheless, it must be remembered that we have only investigated the immediate effects of the device and it is not yet known if training with it has any lasting effects on co-contraction. Additional studies should therefore be made investigating the level of co-contraction during jumps before and after a training intervention with the device.

In the kinematic analysis the first assessment showed that subjects exhibited values that have been associated with an increased risk of knee injury (Hewett, Myer et al. 2005), indicating that the selection process had been successful. The fact that two subjects suffered knee injuries (whereof one was an ACL-injury) during the course of the study further corroborates this. Curiously, the knee abduction values were significantly lower at the second and third assessment. A probable cause for this is the fact that the box that was used for depth jumps was changed after the first assessment. This was done because the first box, that was solid, covered the view of markers on the feet and ankles for some cameras. A “box skeleton” that was almost completely transparent was constructed but with the consequence that it became less stable than the first box, prompting the subjects to step off the box with greater caution which attenuated impact at landing and most likely also the kinematic values. To test this hypothesis we had three random subjects jump from both boxes at our last assessment and then compared the kinematic values attained from each box. Due to data collection errors only two of the subjects’ data could be used however. Results showed that both subjects had greater kinematic values in all variables when using the solid box, corroborating our hypothesis. While more data would be necessary to completely confirm that the switching of boxes was in fact what caused the drastic decrease in knee abduction values it is likely that it had *some* effect on the results and comparisons of the first assessment with the two others are therefore unreliable.

Low adherence rates in the intervention period meant that we could not measure the effects of the device on kinematics. Out of the total 20 training sessions subjects performed on average three. We believe a contributing factor to the low adherence may be that we did not supervise training sessions ourselves. Subjects that are continuously supervised and given positive feedback are more likely to adhere to an exercise regimen compared to subjects without supervision. It has also been shown that subject adherence improves if a close relationship is formed with the supervisors (Sluijs, Kok et al. 1993) which we, with our lack of presence, did not achieve. Time restraints only allowed us to visit the clubs on three random occasions. While the club coaches had agreed to be in charge of supervision when we were not present we feel like this arrangement may not have worked, partly because the coaches also had to supervise regular practices. Ideally, supervision should have been performed by staff related to the study that was not involved in the actual testing (this would have allowed us to reap the benefits of supervision while at the same time blinded the test leaders from the intervention period, preventing them to gain knowledge about subject adherence). Unfortunately we were not in command of such resources. Our strong points when it came to tackling the adherence issue are that we gave clear and standardized instructions and emphasized possible benefits that subjects could experience from training with the device (Jette 1982, Leventhal and Cameron 1987). It is obvious, however, that these measures alone were not enough to achieve satisfying adherence rates. Only two subjects, that for various reasons could not attend regular sports trainings and therefore were given devices to train at home, reported to have performed the required number of sessions. Another advantage with this arrangement was that these subjects did not perform any other type of training thus reducing the number of possible confounding factors. Both subjects decreased some of their dynamic knee abduction movement patterns during the intervention period. However, because there were only two subjects no inferences can be made.

4.1 Conclusion

Performing squats with the new training device stimulates increased hamstring-quadriceps co-contraction and increases the ratio of medial-to-lateral co-contraction. The latter finding may be especially important since female athletes have demonstrated decreased medial-to-lateral co-contraction ratios during athletic activities. Particularly untrained individuals with poor lower extremity control may use the device in the early stages of training to increase knee stability and prepare for demands that jumping and cutting activities may place on the knee. The effects of the device on knee kinematics have yet to be determined.

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