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Off-axis Neuromuscular Training for Knee Ligament Injury Prevention and Rehabilitation

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1. Introduction

Musculoskeletal injuries of the lower limbs are associated with the strenuous sports and recreational activities. The knee was the most often injured body area, with the anterior cruciate ligament (ACL), the most frequently injured body part overall (Lauder et al., Am J Prev. Med., 18: 118-128, 2000). Approximately 80,000 to 250,000 ACL tears occur annually in the U.S. with an estimated cost for the injuries of almost one billion dollars per year (Griffin et al. Am J Sports Med. 34, 1512-32). The highest incidence is in individuals 15 to 25 years old who participate in pivoting sports (Bahr et al., 2005; Griffin et al., 2000; Olsen et al., 2006; Olsen et al., 2004). Considering that the lower limbs are free to move in the sagittal plane (e.g., knee flexion/extension, ankle dorsi-/plantar flexion), musculoskeletal injuries generally do not occur in sagittal plane movements. On the other hand, joint motion about the minor axes (e.g., knee valgus/varus (synonymous with abduction/adduction), tibial rotation, ankle inversion/eversion and internal/external rotation) is much more limited and musculoskeletal injuries are usually associated with excessive loading/movement about the minor axes (or called off-axes) (Olsen et al., 2006; Yu et al., 2007; Olsen et al., 2004; Boden et al., 2000; Markolf et al., 1995; McNair et al., 1990). The ACL is most commonly injured in pivoting and valgus activities that are inherent to sports and high demanding activities, for example. It is therefore critical to improve neuromuscular control of off-axis motions (e.g., tibial rotation / valgus at the knee) in order to reduce/prevent musculoskeletal injuries.

However, there are no convenient and effective devices or training strategies which train off-axis knee neuromuscular control in patients with knee injuries and healthy subjects during combined major-axis and off-axis functional exercises. Existing rehabilitation/ prevention protocols and practical exercise/training equipment (e.g., elliptical machines, stair climbers, steppers, recumbent bikes, leg press machines) are mostly focused on sagittal plane movement (Brewster et al., 1983, Vegso et al., 1985, Decarlo et al., 1992, Howell et al., 1996, Shelbourne et al., 1995). Training on isolated off-axis motions such as rotating/abducting the leg alone in a static seated/standing position is unlikely to be practical and effective. Furthermore, many studies have shown that neuromuscular control is one of the key factors in stabilizing the knee joint and avoiding potentially injurious motions. Practically neuromuscular control is modifiable through proper training

(Myklebust et al., 2003; Olsen et al., 2005; Hewtt et al., 1999; Garaffa et al., 1996). It is therefore very important to improve neuromuscular control about the off-axes in order to reduce knee injuries and improve recovery post injury/surgical reconstruction.

The proposed training program that addresses the specific issue of off-axis movement control during sagittal plane stepping/running functional movements will be helpful in preventing musculoskeletal injuries of the lower limbs during strenuous and training and in real sports activities. Considering that ACL injuries generally do not occur in sagittal plane movement (McLean et al., 2004; Zhang and Wang 2001; Park et al. 2008), it is important to improve neuromuscular control in off-axis motions of tibial rotation and abduction. A pivoting elliptical exercise machine is developed to carry out the training which generates perturbations to the feet/legs in tibial rotations during sagittal plane elliptical movement. Training based on the pivoting elliptical machine addresses the specific issue of movement control in pivoting and potentially better prepare athletes for pivoting sports and helps facilitate neuromuscular control and proprioception in tibial rotation during dynamic lower extremity movements. Training outcome can also be evaluated in multiple measures using the pivoting elliptical machine.

2. Significance for Knee Ligament Injury Prevention/Rehabilitation

An off-axis training and evaluation mechanism could be designed to help subjects improve neuromuscular control about the off-axes external/internal tibial rotation, valgus/varus, inversion/eversion, and sliding in mediolateral, anteroposterior directions, and their combined motions (change the "modifiable" factors and reduce the risk of ACL and other lower limb injuries). Practically, an isolated tibial pivoting or frontal plane valgus/varus exercise against resistance in a seated posture, for example, is not closely related to functional weight-bearing activities and may not provide effective training. Therefore, off-axis training is combined with sagittal plane movements to make the training more practical and potentially more effective. In practical implementations, the off-axis pivoting training mechanism can be combined with various sagittal plane exercise/training machines including the elliptical machines, stair climbers, stair steppers, and exercise bicycles.

This unique neuromuscular exercise system on tibial rotation has significant potential for knee injury prevention and rehabilitation.

1) Unlike previous injury rehabilitation/prevention programs, the training components of this program specifically target major underlying mechanisms of knee injuries associated with off-axis loadings.

2) Combining tibial rotation training with sagittal plane elliptical movements makes the training protocol practical and functional, which is important in injury rehabilitation/prevention training.

3) Considering that tibial rotation is naturally coupled to abduction in many functional activities including ACL injury scenarios, training in tibial rotation will likely help control knee abduction as well. Practically, it is much easier to rotate the foot and adjust tibial rotation than to adduct the knee.

4) Training-induced neuromuscular changes in tibial rotation properties will be quantified by strength, laxity, stiffness, proprioception, reaction time, and instability (back-and-forth variations in footplate rotation) in tibial rotation. The quantitative measures will help us

evaluate the new rehabilitation/training methods and determine proper training dosage and optimal outcome (reduced recovery time post injury/surgery, alleviation of pain, etc.)
5) Success of this training program will facilitate identification of certain neuromuscular risk factors or screening of "at-risk" individuals (e.g. individuals with greater tibial rotational instability and higher susceptibility of ACL injuries); so early interventions can be implemented on a subject-specific basis.
6) The training can be similarly applied to patients post-surgery/post-injury rehabilitation and to healthy subjects for injury prevention.

7) Although this article focuses on training of the knee, the training involves ankle and hip as well. Practically, in most injury scenarios, the entire lower limb (and trunk) in involved with the feet on the ground, so the proposed exercise will likely help ankle/hip training/rehabilitation as well.

3. Pivoting Elliptical System Design

Various neuromuscular training programs have been used to prevent non-contact ACL injury in female athletes (Caraffa et al., 1996; Griffin et al., 2006; Heidt et al., 2000; Hewett et al., 2006; Mandelbaum et al., 2005; Pfeiffer et al., 2006). The results of these programs were mixed; with some showing significant reduction of injury rate and some indicating no statistical difference in the injury rate between trained and control groups. Thus it is quite necessary to design a new system or method with functional control and online assessments. More exercise information will be detected and controlled with this designing system, which will be developed with controllable strengthening and flexibility exercises, plyometrics, agility, proprioception, and balance trainings.

3.1 Pivoting Elliptical Machine Design with Motor Driven

A special pivoting elliptical machine is designed to help subjects improve neuromuscular control in tibial rotation (and thus reduce the risk of ACL injuries in pivoting sports). Practically, isolated pivoting exercise is not closely related to functional activities and may not be effective in the training. Therefore, in this method, pivoting training is combined with sagittal plane stepping movements to make the pivot training practical and functional.

The traditional footplates of an elliptical machine are replaced with a pair of custom pivoting assemblies (Figure.1). The subject stands on each of the pivoting assemblies through a rotating disk, which is free to rotate about the tibial rotation axis. The subject's shoes are mounted to the rotating disks through a toe strap and medial and lateral shoe blockers, which makes the shoe rotate together with the rotating disk while allowing the subject to get off the machine easily and safely. Each rotating disk is controlled by a small motor through a cable-driven mechanism. An encoder and a torque sensor mounted on the servomotor measure the pivoting angle and torque, respectively. A linear potentiometer is used to measure the linear movement of the sliding wheel on the ramp and thus determine the stride cycle of the elliptical movement. Practically, the pivoting elliptical machine involves the ankle and hip as well as the knee. Considering that the entire lower extremities and trunk are involved in an injury scenario in pivoting movements, it is appropriate to train the whole lower limb together instead of only training the knee. Therefore, the proposed training will be useful for the purpose of rehabilitation after ACL reconstruction with the multiple joints of the lower limbs involved. Mechanical and electrical stops plus enable switch will be used to insure safe pivoting. Selection of a small but appropriately sized motor with 5~10 Nm torque will make it safe for the off-axis loading to the knee joint and the whole lower limb.

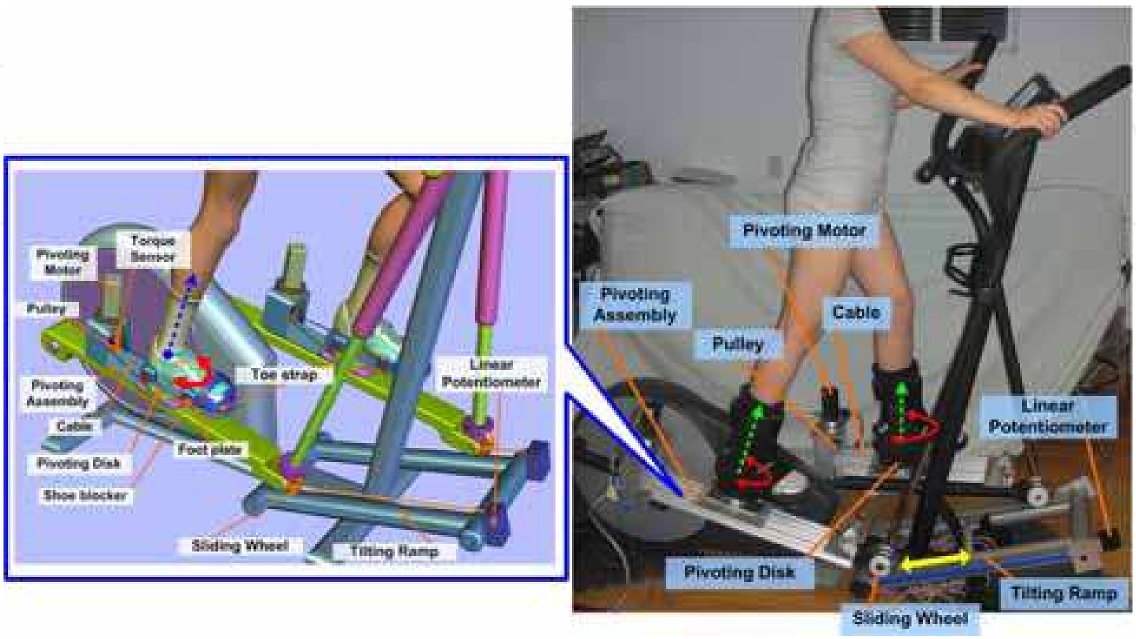


Fig. 1. A pivoting elliptical machine with controlled tibial rotation (pivoting) during sagittal stepping movement. The footplate rotation is controlled by two servomotors and various perturbations can be applied flexibly

3.2 Design Pivoting Training Strategies

The amplitude of perturbation applied to the footplate rotation during the elliptical movement starts from moderate level and increase to a higher level of perturbations, within the subject's comfort limit. The subjects are encouraged to exercise at the level of strong tibial rotation. The perturbations can be adjusted within pre-specified ranges to insure safe and proper training. If needed, a shoulder-chest harness can be used to insure subject's safety.

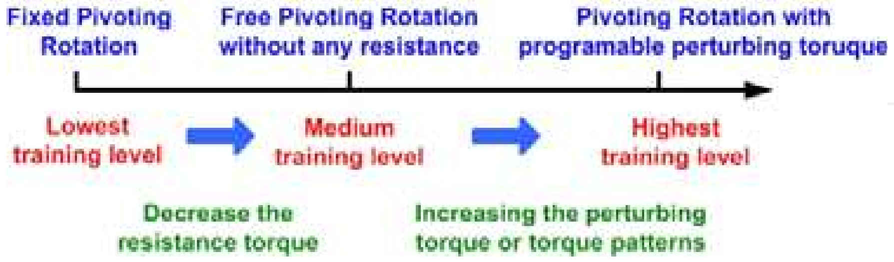


Fig. 2. the main principle of the training challenge levels

Figure 2 shows the main principle of the training challenge levels involved in the off-axis training. The flowchart will help the subject/operator decide and adjust the training/challenge levels. The subject can also reach their effective level by adjsuting the challenge level.

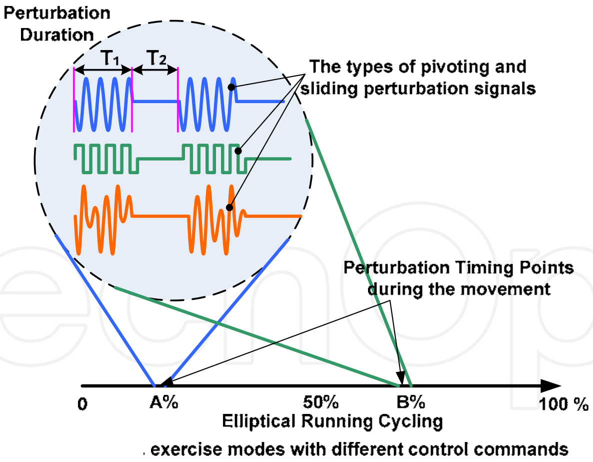


Fig. 3. Elliptical Running Cycling exercise modes with different control commands

Sinusoidal, square and noise signals will be considered to generate perturbation torque commands, which control the pivoting movements, as shown in Figure 3. The subject is asked to resist the pivoting perturbations and keep the foot at the neutral target position in the VR environment during the elliptical stepping/running movement.

The duration, interval, frequency and amplitude of each control signal are adjusted by the microcontroller. As the exercise feedback, the instability of the lower limb perturbation will be displayed on the screen. In addition, the specific perturbation timing during the stepping/running movement will be controlled according to the different percentage of the stepping/running cycling (e.g. A%, B%), as shown in Figure 3. The different torque comands will provide different intensities and levels of the lower limb exercise.

According to the the training challenge levels, two training modes have been developed. The operation parameters for the trainers and therapists would be optimized and siplimfied, so that it would be easy for the users to understand and adjust to the proper training levels. We put those optimized parameters on the control panel as the default parameters and also create a "easy-paraterm" with 10 steps for quick use.

Training Mode 1: The footplate is perturbed back and forth by tibial rotation (pivoting) torque during the sagittal plane stepping/running movement. The subject is asked to resist the foot/tibial rotation torque and keep the foot pointing forward and lower limb aligned properly while doing the sagittal movements. Perturbations are applied to both footplates simultaneously during the pivoting elliptical training. The perturbations will be random in timing or have high frequency so the subject can not predict and reaction to the individual perturbation pulses. The tibial rotation/mediolateral perturbation torque/position amplitude, direction, frequency, and waveform can be adjusted conveniently. The perturbations will be applied throughout the exercise but can also be turned on only for selected time if needed.

Training Mode 2: The footplate is made free to rotate (through back-drivability control which minimizes the back-driving torque at the rotating disks or by simply releasing the cable driving the rotating disk) and the subject needs to maintain stability and keep the foot straight during the elliptical stepping exercise. Both of the modes are used to improve neuromuscular control in tibial rotation (Fig. 4).

To make the training effective and keep subjects safe during the pivoting exercise, specific control strategies will be evaluated and implemented. Pivoting angle, resistant torque, reaction time and standard deviation of the rotating angle, those above recording information will be monitored to insure proper and safe training. The system will return to the initial posture if one of those variables is out of range or reaches the limit.

(a) Training Mode (b) Evaluation Mode

Fig. 4. The pivoting elliptical machine with controlled tibial rotation during sagittal plane elliptical running movement. The footplate rotation is controlled by a servomotor and various perturbations are applied. The EMG measurement is measured for the evaluation.

3.3 Using Virtual Reality Feedback to Guide Trainers in Pivoting Motion

Real-time feedback of the footplate position is used to update a virtual reality display of the feet, which is used to help the subject achieve proper foot positioning (Fig. 5). A web camera is used to capture the lower limb posture, which is played in real-time to provide qualitative feedback to the subject to help keep the lower limbs aligned properly. The measured footplate rotation is closely related to the pivoting movements. The pivoting training using the pivoting device may involve ankle and hip as well as the knee. However, considering the trunk and entire lower extremities are involved in an injury scenario in pivoting sports, it is more appropriate to train the whole lower limb together instead of training the knee in isolation. Therefore, the pivot training is useful for the purpose of lower limb injury prevention and/or rehabilitation with the multiple joints involved.

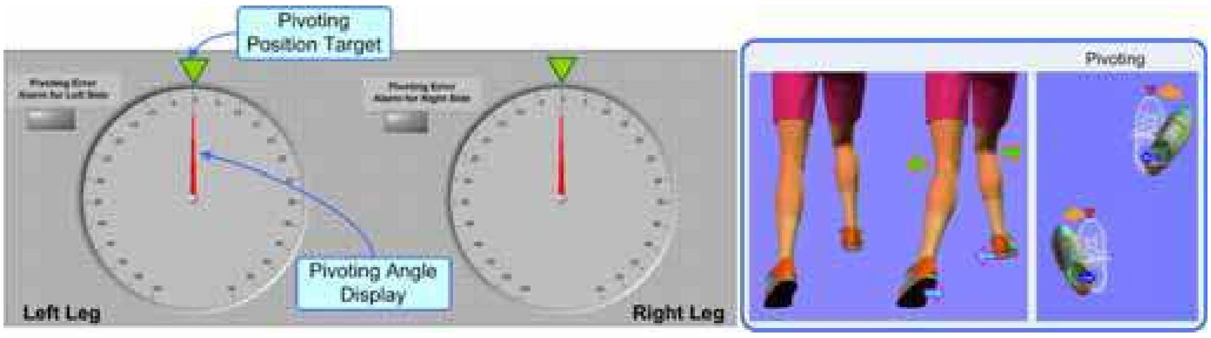


Fig. 5. Real-time feedback of the footplate position is used to update a virtual reality display of the feet, which is used to help the subject achieve proper foot positioning

A variety of functional training modes have been programmed to provide the subjects with a virtual reality feedback for lower limb exercise. The perturbation timing of pivoting movements will be adjusted in real-time to simulate specific exercise modes at the proper cycle points (e.g. A%, B%), as shown in Figure 3. According to the VR feedback on the screen, the subjects need to give the correct movement response to maintain the foot pointing forward and aligned with the target position for neuromuscular control training of the lower limbs (Fig. 5). The VR system shows both the desired and actual lower limb posture/foot positions according to signals measured in real time, the subject needs to correct their running or walking posture to track the target (Fig. 5)

4. Evaluation Method Design and Experimental Results

4.1 Evaluation Method for the neuromuscular and biomechanical properties of the low limb with the pivoting train

The neuromuscular and biomechanical properties could be evaluated as follows:

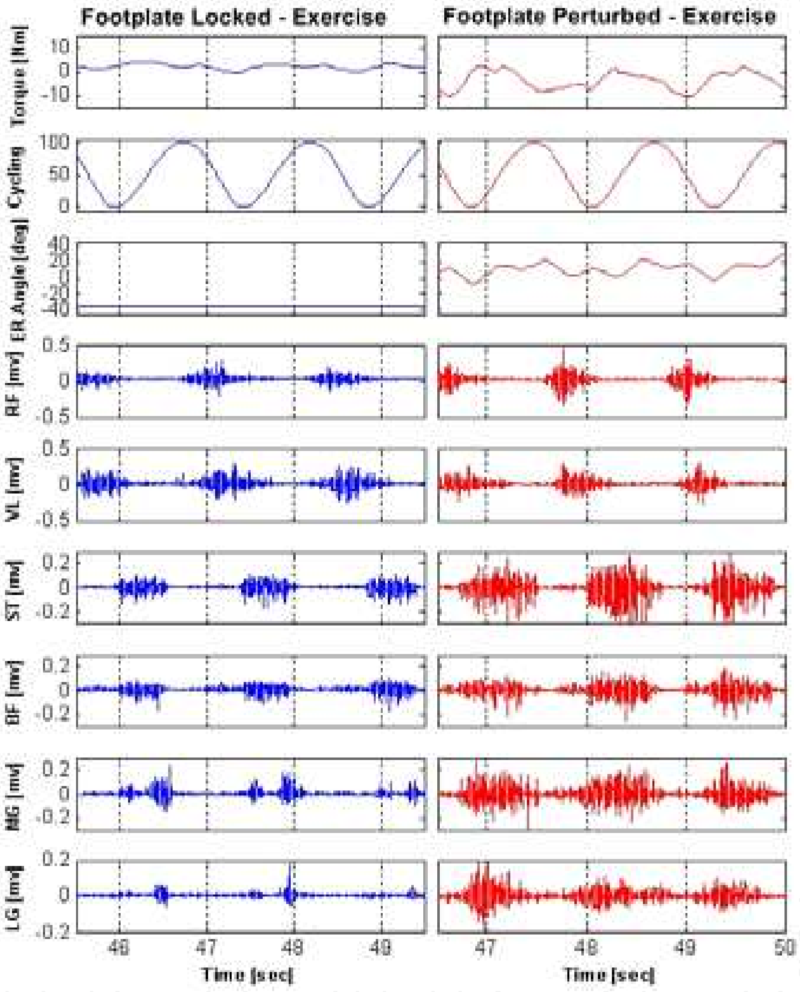
The subject will stand on the machine with the shoes held to the pivoting disks. The evaluations can be done at various lower limb postures. Two postures are selected. First, the subject stands on one leg with the knee at full extension and the contralateral knee flexed at about 45°. Measurements will be done at both legs, one side after the other. The flexed knee posture is helpful in separating the tibial rotation from femoral rotation, while the extended side provides measurements of the whole lower limb. The second posture will be the reverse of the first one. The testing sequence will be randomized to minimize learning effect. Several measures of neuromuscular control in tibial rotation could be taken at each of the postures as follows:

1. ***Stiffness:*** At a selected posture during the elliptical running movement, the servomotor will apply a perturbation with controlled velocity and angle to the footplate, and the resulting pivoting rotation and torque will be measured. Pivoting stiffness will be determined from the slope of the torque-angle relationship at the common positions and at controlled torque levels (Chung et al., 2004; Zhang and Wang 2001; Park et al. 2008).
2. ***Energy loss:*** For joint viscoelasticity, energy loss will be measured as the area enclosed by the hysteresis loop (Chung et al., 2004).
3. ***Proprioception:*** The footplate will be rotated by the servomotor at a standardized slow velocity and the subject will be asked to press a handheld switch as soon as she feels the movement. The perturbations will be applied randomly to the left or right leg and internal or external rotation. The subject will be asked to tell the side and direction of the slow movement at the time she presses the switch. The subject will be blind-folded to eliminate visual cues.
4. ***Reaction time*** to sudden twisting perturbation in tibial rotation: Starting with a relaxed condition, the subject's leg will be rotated at a controlled velocity and at a random time. The subject will be asked to react and resist the tibial rotation as soon as he feels the movement. Several trials will be conducted, including both left and right legs and both internal and external rotation directions.
5. ***Stability (or instability)*** in tibial rotation will be determined as the variation of foot rotation (in degrees) during the elliptical running movement.

Muscle strength will be measured while using the pivoting elliptical machine. With the pivoting disk locked at a position of neutral foot rotation, the subject will perform maximal voluntary contraction (MVC) in tibial external rotation and then in tibial internal rotation. The MVC measurements will be repeated twice for each direction.

4.2 Experimental Results: 1. Muscle activities

The subjects performed the pivoting elliptical movement naturally with rotational perturbations at both feet. The perturbations resulted in stronger muscle activities in the targeted lower limb muscles. Compared with the trial of the footplate-locked exercise (e.g. like an original elliptical exerciser), the hamstrings and gastrocnemius which have considerable tibial rotation action showed considerably increased actions during forward stepping movement with the sequence of torque perturbation pulses (Fig. 6). for example, comparing Fig. 6b. LG/MG EMG plots with Fig. 6a.



(a) (b)

Fig. 6. A subject performed the pivoting elliptical exercise using the pivoting elliptical machine. (a) The footplates were locked in the elliptical movement. (b) The footplates were perturbed by a series of torque pulses which rotate the footplates back and forth. The subject was asked to perform the elliptical movement while maintaining the foot pointing forward. From top to bottom, the plots show the footplate external rotation torque (tibial internal rotator muscle generated torque was positive), sliding wheel position (a measurement of elliptical cycle), footplate rotation angle (external rotation is positive), and EMG signals from the rectus femoris (RF), vastus lateralis (VL), semitendinosus (ST), biceps femoris (BF), medial gastrocnemius (MG), and lateral gastrocnemius (LG).

4.3 Experimental Results: Stability in tibial rotation

Three female and 3 male subjects were tested to improve their neuromuscular control in tibial rotation (pivoting). Subjects quickly learned to perform the elliptical movement with rotational perturbations at both feet naturally. The pilot training strategies showed several training-induced sensory-motor performance improvements. Over five 30-minute training sessions, the subjects showed obvious improvement in controlling tibial rotation, as shown in the reduced rotation instability (variation in rotation) (Fig. 7).

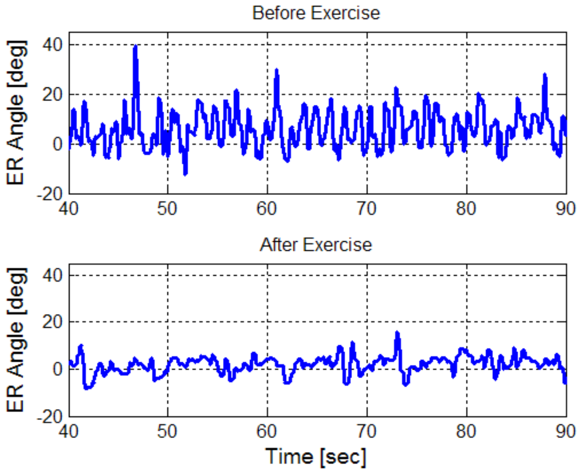


Fig. 7. Stability in tibial rotation with the footplate free to rotate during the pivoting elliptical exercise before and after 5 sessions of training using the pivoting elliptical machine. The data are from the same female subject. Notice the considerable reduction in rotation instability variation and thus improvement in rotation stability.

The pivoting disks were made free to rotate and the subject was asked to keep the feet stable and pointing forward during the elliptical movements. Standard deviation of the rotating angle during the pivoting elliptical exercise was used to measure the rotating instability, which was reduced markedly after the training (Fig. 7), and the instability reduction was obvious for both left and right legs (Fig. 8).

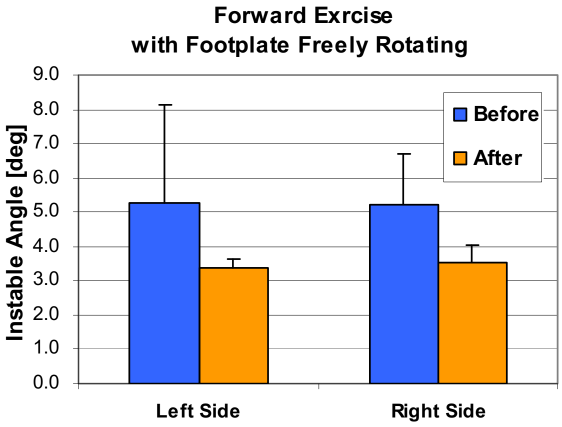


Fig. 8. Rotation instability of a female subject before and after 5 sessions of training during forward elliptical exercise with foot free to rotate. Similar results were observed in backward pivoting elliptical movements.

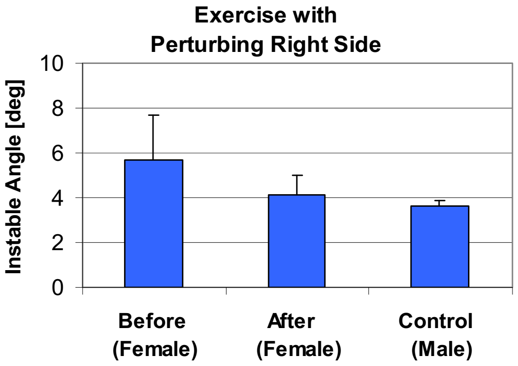


Fig. 9. Rotation instability of multiple subjects before and after 5 sessions of training during forward pivoting elliptical exercise with footplate perturbed in rotation by the servomotor.

Relevant improvement for rotation stability of the lower limb was observed when measured under external perturbation of the footplate by the motor, as shown in Fig.9, which also showed higher rotation instability of females as compared with males. The increased stability following the training may be related to improvement in tibial rotation muscle strength, which was increased after the training of multiple sessions.

4.4 Experimental Results: Proprioception and Reaction time in sensing tibia/footplate rotation

The subjects stood on the left leg (100% body load) on the pivoting elliptical machine with the right knee flexed and unloaded (0% body load). From left to right, the 4 groups of bars correspond to the reaction time for external rotating (ER) the loaded left leg, the reaction time for internal rotating (IR) the loaded left leg; the reaction time for external rotating the unloaded right leg; and the reaction time for internal rotating the unloaded right leg.

Proprioception in sensing tibia/footplate rotation also showed improvement with the training, as shown in Fig. 10. In addition, reaction time tends to be shorter for the loaded leg as compared to the unloaded one and tendency of training-induced improvement was observed (Fig. 11). Statistical analysis was not performed due to the small sample size in the pilot study.

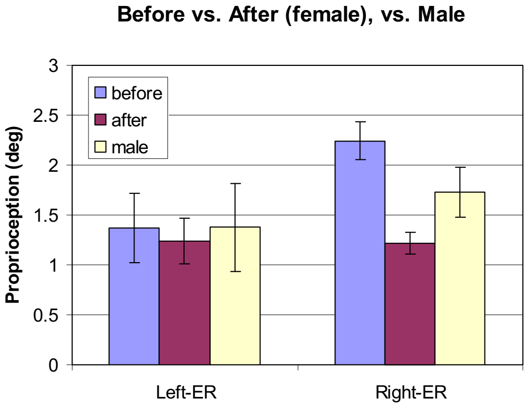


Fig. 10. Proprioception in sensing tibia/foot rotation before and after 5 sessions of training, and the males (before training only)

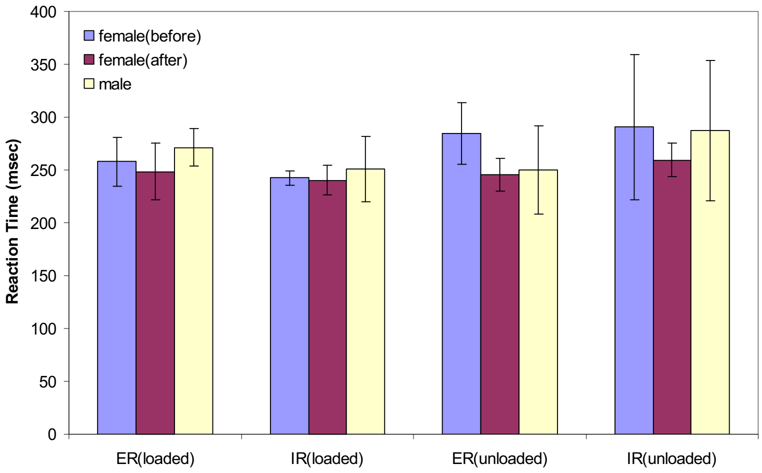


Fig. 11. Reaction time of the subjects (mean±SD) to sudden external rotation (ER) and internal rotation (IR) perturbations before and after training.

5. Discussion

A number of treatment strategies are available for ACL injuries (Caraffa et al., 1996; Griffin et al., 2006; Heidt et al., 2000; Hewett et al., 2006; Hewett et al., 1999; Mandelbaum et al., 2005; Myklebust et al., 2003; Petersen et al., 2005; Pfeiffer et al., 2006; Soderman et al., 2000). It appears that the successful programs had one or several of the following training components: traditional strengthening and flexibility exercises, plyometrics, agility, proprioception, and balance trainings. Some programs also included sports-specific technique training.

Improper neuromuscular control and proprioception are associated with ACL injuries, and therefore relevant training was conducted for ACL injury prevention and rehabilitation (Griffin et al., 2006; Caraffa et al., 1996). Griffin and co-workers reviewed some of the applied prevention approaches (the 2005 Hunt Valley Meeting). The general outcome is that neuromuscular training reduces the risk of ACL injuries significantly, if plyometrics, balance, and technique training were included.

In the current exercise machine market, the elliptical machine, stepper, and bicycle do not provide any controllable pivoting functions, therefore they are not suitable for off-axis neuromuscular training for ACL injury rehabilitation/prevention. The current clinical and research market needs a system which can not only implement the existing treatments and prevention strategies but also perform off-axis rotation training for the knee injury prevention and rehabilitation. Our controllable training system with quantitative outcome evaluation will offer various training modes including traditional strengthening and flexibility exercises, plyometrics, agility, proprioception, balance trainings and sports-specific technique training. Additionally the success of this project will offer the researchers a new tool to conduct further quantitative study in the field.

Tibial rotation training using the pivoting elliptical machine may involve ankle and hip as well as the knee. However, considering the trunk and entire lower extremities are involved in an injury scenario in pivoting sports, it is more appropriate to train the whole lower limb together instead of training the knee in isolation. Therefore, the pivot training is useful for the purpose of ACL injury prevention with the multiple joints involved.

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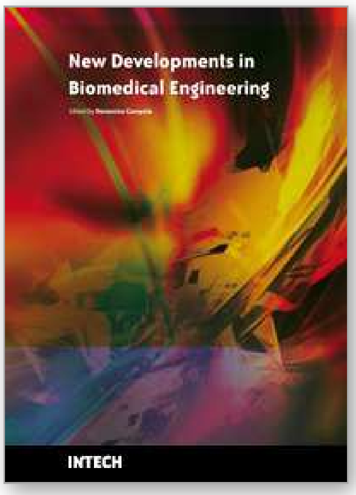

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Biomedical Engineering is a highly interdisciplinary and well established discipline spanning across engineering, medicine and biology. A single definition of Biomedical Engineering is hardly unanimously accepted but it is often easier to identify what activities are included in it. This volume collects works on recent advances in Biomedical Engineering and provides a bird-view on a very broad field, ranging from purely theoretical frameworks to clinical applications and from diagnosis to treatment.

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