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Offaxis Neuromuscular Training of Knee Injuries using an Offaxis Robotic Elliptical trainer

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***Abstract*— The goal of this study was to use an offaxis robotic elliptical trainer to improve off-axis neuromuscular control in people with knee injuries. Thirteen individuals with knee injuries participated in the study. Among them, 8 individuals participated in 18 sessions of pivoting offaxis intensity-adjustable neuromuscular control training (POINT) (3 sessions/week for 6 weeks including 3 evaluation sessions) to improve offaxis neuromuscular control, specifically dynamic lower limb stability in pivoting. 5 individuals served as controls who only participated in the three evaluations. Following POINT patients in the training group reduced pivoting instability (p=0.024), while the control group did not (p=0.118). Individuals in the training group were able to hop farther in a single leg hop for distance task, take shorter in 12m hop time for time task, and reported reduced knee pain. The results suggest that subject-specific POINT utilizing the novel robotic elliptical trainer can be implemented as a rehabilitation protocol for patients with knee injuries to improve their lower limb functions and reduce knee symptoms.**

I. Introduction

KNEE joint is vulnerable to both acute and chronic injuries. Particularly, anterior cruciate ligament (ACL), one of four ligaments inside the knee, is most frequently injured ligament during sports and recreational activities [1]. Similarly, patellofemoral pain syndrome (PFPS), pain originating from the patellofemoral joint and associated structures excluding other intra-articular and peripatellar pathology, occurs in 16-25 percent of all injuries in runners and 11 percent of musculoskeletal complaints [2-4]. Following ACL injury, individuals often experience deterioration of knee stability and they may develop compensatory mechanisms such as increased tibial external rotation to avoid stretching a partially torn ACL or loss of stability related to ACL rupture [5]. On the other hand, patients with PFPS show imbalance of the musculoskeletal system around knee including magnitudes and directions of forces from the soft tissue structures, such as quadriceps muscles, patellar and quadriceps tendons. Such imbalance including imbalanced contraction timing between Vastus medialis oblique (VMO) and vastus lateralis (VL) may lead to patellar maltracking and knee pain [6-10]. Following aformentioned knee injury or pain, daily activities of people with knee injuries or disorders are limited due to joint instability and abnormal movement patterns associated with knee pain but also they are predisposed to development in arthritis and permanet disability [4, 6-7, 11].

Previous literature suggests that re-establishing neuromuscular control of the lower extremity following knee injuries is important to restore dynamic joint stability and movement patterns [12]. Neuromusuclar control is necessary to maintain posture and economically efficient movements during daily activities without causing any musculoskeletal injuries [6-7, 13-14]. In order to re-establish neuromuscular control of the lower extremity, neuromuscular training has been applied to patients with ACL injury or PFPS. Following neuromuscular training, patients who received ACL reconstruction significantly improved Cincinnati Knee Scores and VAS scores for global knee function. On the other hand, Cowan et al found that neuromuscular training among PFPS patients altered the motor control of VMO related to VL and reduced pain [15].

Although neuromuscular training showed positive outcomes from previous studies, other literature reported contradicting results in which both exercise and non-exercise group in PFPS patients reduced knee pain similarly [16]. Such contradicting results in rehabilitation for people with knee injuries or disorders may be related to the tasks utilizing for neuromuscular training. Most of neuromuscular training programs have been designed to improve knee function based on the sagittal plane of movements. However, the function of ACL is to constrain anterior tibial translation and tibial internal rotation related to femur and PFPS is related to imbalance of the musculoskeletal system around knee. Thus, assessing and improving *offaxis neuromuscular control*, an ability to control pivoting directions of movements, under functionally relevant conditions can be more effective for patients to reduce individuals' knee symptoms and improve overall lower extremity function. However, there is a lack of tool to assess individuals' offaxis neuromuscular control from offaxis neuromuscular training and a lack of rehabilitation device targeting subject-specific needs for offaxis neuromuscular control training to improve their neuromuscular control of multi-planes of movements.

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The goal of this study was to use an intensity adjustable offaxis robotic elliptical trainer to improve offaxis neuromuscular control through subject-specific 6-week pivoting offaxis intensity-adjustable neuromuscular control training (POINT) in subjects with knee injuries.

II. MATERIALS AND METHODS

A. Device description

The offaxis robotic elliptical trainer allows individuals to have an opportunity to control pivoting and medio-lateral sliding movements, *offaxis neuromuscular control* [17]. Based on such unique opportunity to investigate offaxis neuromuscular control, training and evaluating offaxis neuromuscular control of lower extremity is possible. Two unique mechanisms of the offaxis robotic elliptical trainer make it possible to perform subject-specific training based on evaluations on the offaxis robotic elliptical trainer: 1) cable driven mechanisms with servomotors which control pivoting movements and 2) linear guides with servomotors which control medio-lateral sliding movements (Fig. 1). These motors generated adequate torques depending on our desirable tasks using Labview program (National Instruments™, Austin, TX, USA). Each of the four servomotors has a built-in encoder to measure the motor rotation or displacement. In addition to such two unique mechanisms of the offaxis robotic elliptical trainer, audio-visual biofeedback including individuals' foot and target position, and sounds if individuals' foot position is out of the target position, make the evaluation and training more effective (Fig. 2). A potentiometer was attached to the small wheel on the ramp of the elliptical trainer to measure the stepping cycle of the elliptical trainer.

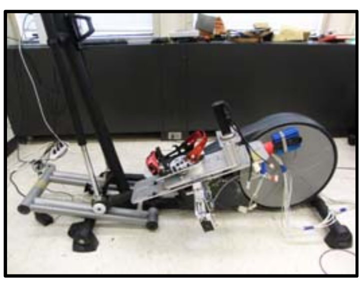

Fig.1. Offaxis robotic elliptical trainer

B. Participants and training protocol

Thirteen patients with knee injury or disorder (Table1) participated in the study. Prior to the experiments, all subjects read and signed an informed consent approved by the institutional review board of Northwestern University. The inclusion criteria of this study were to have knee injury or knee pain including ACL injury, patellofemoral pain syndrome (PFPS). The exclusion criteria of this study were individuals who were 1) unable to stand/exercise on the elliptical machine for 40 minutes; 2) with neurological disorders; 3) with heart conditions not suitable to do strenuous physical exercises.

Among thirteen patients, eight patients were in the training group who participated in 15 sessions of six week subject-specific POINT, and three time evaluations (E1: pre training evaluation, E2: mid training evaluation, E3:post training evaluation). Among eight patients, one patient finished his study as 9 sessions since he did not feel to need further training for his knee. Each training session took about half an hour including 1) generating stepping movements without footplate rotation and 2) maintaining feet straight positions while participants generated stepping movements under the condition in which the footplates were free to rotate with low friction (free rotation mode), 3) assistive spring force, 4) were perturbed in pivoting with sinusoidal perturbation torque and offset torque in internal or external rotation. Depending on subject's capability to perform the task without perceiving any knee pain or fatigue, 4th condition may not be included during earlier sessions and gradually increased the difficulty of tasks by adjusting peak sinusoidal perturbation and offset torque. On the other hand, five patients were in the control group who came to our lab three times for evaluations only during the six week period. Even though the elliptical trainer has been widely used for exercise, individuals might fall down if losing their balance. Thus, for the safety reason, each participant wore a chest-shoulder harness throughout sessions to prevent falling. During the evaluation sessions, individuals held the handles for balance as seen from Fig 2 to minimize potential influence of upper body activities to lower limb biomechanics. Since the goal of our study was to evaluate the feasibility of assessing and improving offaxis neuromuscular control on the novel offaxis robotic elliptical trainer, each group was compared separately as a within group study design.

C. Outcome Evaluation

Three evaluations including pre, mid, post training have been performed to identify the effect of training on off-axis neuromuscular control, particularly pivoting instability. Furthermore, functional activities and self-reported questionnaire were compared before, after, and 6 week after POINT among subset of individuals (3 individuals) who participated in the training study. Functional activities include 10m walk for time, 12m hopping for time and single leg hop for distance were performed at subjects' comfortable level in order to ensure that the improvement from POINT can be functionally beneficial to patients with knee injuries or disorders. Furthermore, subjects also filled self-reported questionnaires such as KOOS (Knee injury and Osteoarthritis Outcome Score).

Fig. 2. Subject with bio- audiovisual feedback

TABLE I
PARTICIPANTS CHARACTERISTICS

Subject	Group	Sex	Age	Injury or Symptom
1	Training	M	29	L: MCL rupture and ACL injury
2	Training	M	39	R: Both PFPS
3	Training	M	65	R: Patellar tendonitis
4	Training	F	24	L: ACL injury
5	Training	F	24	L: ACL injury
6	Training	M	45	L: ACL injury
7	Training	F	20	R: ACL injury
8	Training	F	25	L:PFPS
9	Control	F	23	L: ACL
10	Control	F	24	R: PFPS
11	Control	F	24	L: PFPS
12	Control	M	32	L: ACL injury
13	Control	M	64	L: Meniscus tear

D. Data processing

Pivoting instability is introduced to characterize offaxis neuromuscular control, specifically dynamic lower limb stability in pivoting. During functional activities, proper feet contacts on the ground are essential. It is advised that feet positions should point to the progression of walking or other activities. Thus, with challenging haptic feedback (such as free rotation task), dynamic lower limb stability of patients can be quantified under a safe controlled environment to assess their abilities of trying their correct lower limb posture (both feet straight) during stepping movements. Pivoting instability is defined as the standard deviation of footplate rotation angle (1) while individuals have to maintain their targeted posture (second toe over the knee cap) during the tasks. The reason we chose standard deviation of angle over mean angle or root mean square of angle to characterize pivoting instability is that individuals have their own natural foot posture during the tasks, which corresponds to offset of the variance value. In other words, mean or root mean square of rotation angles includes subject to subject variations. Thus, mean can be taken out as a way of normalization to compare the effect of training on task performance between subjects.
Since stepping movements include different characteristics of weight bearing condition on each lower limb, four phases were defined to investigate the effect of phase on pivoting instability (Fig. 3). As seen in Fig 3, four phases were defined adapting from a similar method during cycling based on the signal from the potentiometer measuring foot stepping cycle. Pivoting instability was defined as below to characterize the effect of each stepping cycle and each phase.

$$Pivoting\ \ Instability\,(k) = \sqrt{\sum_{j=1}^{M_k} (Y_k(j) - \overline{Y_k(j)})^2 M_k^{-1}}\ , \quad (1)$$

$$Y_k(j) = \sum_{i=1}^{N_{jk}} \theta_{jk}(i) N_{jk}^{-1}\text{, and}$$

N and i denote total and each data point per phase at each cycle, respectively; M and j total and each number of stepping cycle, respectively; Θ and k footplate rotation angle and each phase, respectively. Since each individual's knee was in a different symptomatic condition, we chose free rotation mode as an assessment task to quantify pivoting instability because all subjects were able to perform the task in a controlled manner at their comfortable stepping speeds for a minute.

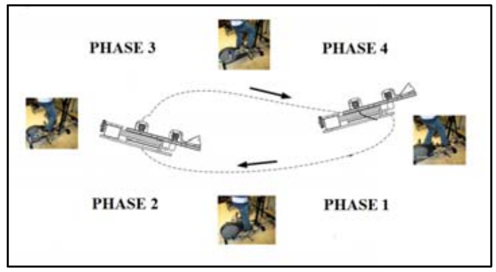

Fig. 3. Four phases of elliptical cycle.

E. Statistics

Repeated measures tests for each group were performed to investigate the effect of POINT on pivoting instability. Within group factors were phases of the elliptical cycle and evaluations. If sphericity was violated, greenhouse-geisser correction was used. P value was 0.05.

III. RESULTS

Pivoting instability of the symptomatic side was significantly reduced following six week POINT (p=0.024) (Fig. 4 and Fig. 5). On the other hand, control group (Fig. 4 and Fig. 6) did not show significant difference in pivoting instability among three evaluations (p=0.118). Both groups did not show significant difference in pivoting instability between four different phases of elliptical cycle. There were no interactions between evaluations and phases in both groups.

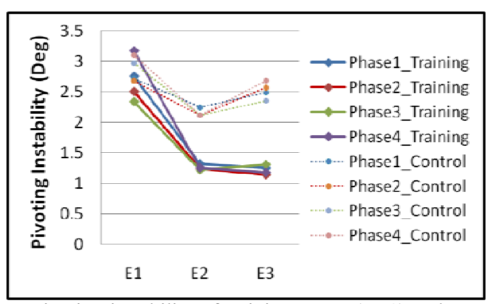

Fig.4. Mean pivoting instability of training group (N=8) and control group (N=5) for three evaluations per each phase.

Subject 2 took shorter time for 12 m hop for time in his symptomatic side without knee pain (from 5.74s to 4.93s) but not much difference in single leg hop for the time (Table II). Subject 3 who was not able to perform 12m hop for time task at his first evaluation, was able to perform the task following POINT. Subject 3 improved single leg hop for distance in his symptomatic side following POINT and maintained farther hop distance at the six week follow-up than the hop distance at the pre POINT evaluation (Table II).

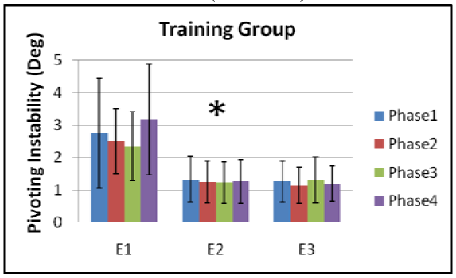

Fig.5. Pivoting instability from the training group (N=8) at each phase in the three evaluations. Each error bar indicates ±1STD.

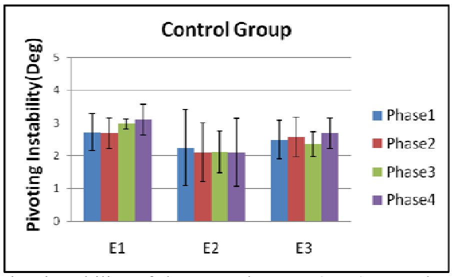

Fig. 6. Pivoting instability of the control group (N=5) at each phase in the three evaluations. Each error bar indicates ±1STD.

Subject 7 was not able to perform 12m hop for time task at the pre and post POINT evaluation, yet she was able to perform at the six week follow up (Table II). All three individuals were showing a trend of improving KOOS score (subject2: from 128 to 131, subject3: from 124 to 144, subject 7: from 96 to 119 out of 168).

TABLE II.
SINGLE LEG HOP FOR DISTANCE IN SYMPTOMATIC SIDE

Subjects	Symptoms	Single Leg Hop for Distance (Cm)		
		Pre	Post	6 week follow-up
2	R: Both PFPS	124.14	122.87	NA
3	R: Patellar tendonitis	91.4	128.27	116.8
7	R: ACL injury	Not able to perform	33.02	60.96

NA denotes not available.

IV. CONCLUSION

In comparison to the trend of three evaluations among individuals in the control group, participants in the training group reduced their pivoting instability significantly following subject-specific POINT. Based on functional tasks from the subset of individuals in the training group, following POINT they were able to perform better in functional tasks without complaining knee pain or any fear of collapsing. In addition, they reported higher score in KOOS following POINT. Our positive effect of POINT utilizing an intensity adjustable offaxis robotic elliptical trainer may be feasible for a subject specific rehabilitation in individuals with knee injuries and knee disorders. In the future, detailed subject population researches with matched control groups are necessary to investigate more targeted and optimized protocol for rehabilitation in patients with each knee injury or disorder and understanding underpinning risk factors or neuromuscular mechanisms of each knee injury or disorders.

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