A Pivoting Elliptical Training System for Prevention and Rehabilitation of Musculoskeletal Injuries

Yupeng Ren
Sensory Motor Performance Program
RIC
Chicago IL, USA
yupeng.r@gmail.com

Song Joo Lee
Dept. of Biomedical Eng.
Northwestern Univ.
Evanston IL, USA
song-lee@northwestern.edu

Hyung-Soon Park
Sensory Motor Performance Program/Dept. of Physical Med & Rehab
RIC/Northwestern Univ.
Chicago IL, USA

Li-Qun Zhang
Depts. Of Physical Med & Rehab, Orthopaedic Surgery and Biomedical Engineering
RIC/Northwestern Univ.
Chicago IL, USA
l-zhang@northwestern.edu

***Abstract*— Knee injuries often occur in pivoting activities but most existing training and rehabilitation devices mainly allow sagittal movements. Thus, a pivoting elliptical training system (PETS) was developed to train and evaluate neuromuscular control in pivoting directions, pivoting neuromuscular control, for prevention and rehabilitation of musculoskeletal injuries. PETS included capabilities of controlling two footplates individually or simultaneously through servomotor controls so that the footplates behaved like two torsional springs, created a slippery surface, or perturbed. Feasibility of PETS to improve pivoting neuromuscular control and neuromechanical properties was demonstrated through experiments on selected healthy individuals. They improved pivoting neuromuscular control in terms of pivoting instability, and reduced reaction time and proprioceptive acuity following training. Thus, PETS can potentially be used as a therapeutic and research tool to investigate underlying mechanisms of pivoting-related injuries and to train human subjects to improve neuromuscular control during risky pivoting movements.**

Keywords*— *Musculoskeletal injury prevention and rehabilitation; Pivoting control; Therapeutic Intervention

I. INTRODUCTION

Musculoskeletal injuries of the lower limb are associated with inadequate neuromuscular control under unstable circumstances (e.g., external perturbation, slippery or rocky surfaces) during strenuous sports and recreational activities [1, 2]. Among the musculoskeletal injuries, anterior cruciate ligament (ACL) is the most frequently injured ligament, leading to long-term diseases such as knee osteoarthritis (OA) [2, 3]. Although the major motion of the knee is flexion/extension in the sagittal plane, injuries usually do not occur in flexion/extension. In contrast, offaxis motion of the knee (axial plane pivoting or tibial rotation and frontal plane abduction/adduction) is much more limited and excessive loadings about the offaxes may be closely associated with knee injuries [3]. For example, the highest incidence is in individuals 15 to 25 years old who participate in *pivoting* sports [4], which involve tibial rotation and coupled valgus/varus loadings. Therefore, the abilities of controlling offaxis movements, *offaxis neuromuscular control* is essential in preventing knee injuries. Thus, training utilizing movements in the sagittal plane alone may not allow individuals to learn offaxis neuromuscular control strategies for injury prevention [2, 3]. Considering musculoskeletal injuries of lower limbs often occur in *pivoting sports* including basketball, soccer, volleyball and handball, it is important to train individuals improving offaxis neuromuscular control in functionally relevant tasks involving offaxis as well as sagittal flexion/extension motions under weight-bearing.

It is therefore critical to improve neuromuscular control of off-axis motions in order to reduce and rehabilitate ACL and other knee injuries. However, existing exercise/rehabilitation focuses on sagittal plane movement and there is a lack of effective protocols and practical equipment to prevent and rehabilitate people for strenuous and high-risk off-axis activities. Currently, most prevention and rehabilitation devices (such as treadmills, steppers, or elliptical trainers) allow individuals to improve lower limb functions mainly utilizing movements in sagittal planes (major axis movements) without intending to assess and improve pivoting neuromuscular control. Furthermore, previous studies reported that in comparison to the earlier stage rehabilitation, the progression of the later stage rehabilitation is often vague and less structured, and is usually based on the individual's motivation. Especially, 1) there is a lack of quantification tools to assess functional improvement during the later stage in rehabilitation, 2) a lack of criteria when individuals could be back to their sports with appropriate dynamic stability, muscle strength, and power, and 3) a lack of focus on individuals' needs with specific biofeedback or encouragement [3, 5]. In addition, previous studies have been neglected to investigate global measures such as endpoint kinematics and kinetics (e.g. foot pivoting angle or stability) as a result of contributions from multi-joint kinetic chain (ankle, knee, hip, and trunk), which are highly related to injury scenarios and closed-chain exercises [6, 7].

The purpose of this study was to develop a pivoting elliptical training system (PETS) that had the capabilities of 1) controlling pivoting movements while subjects step in the sagittal plane and receive biofeedback for effective training, 2) providing various training modes, and 3) conducting outcome evaluations in pivoting as well as sagittal stepping. Feasibility of PETS to improve pivoting neuromuscular control and

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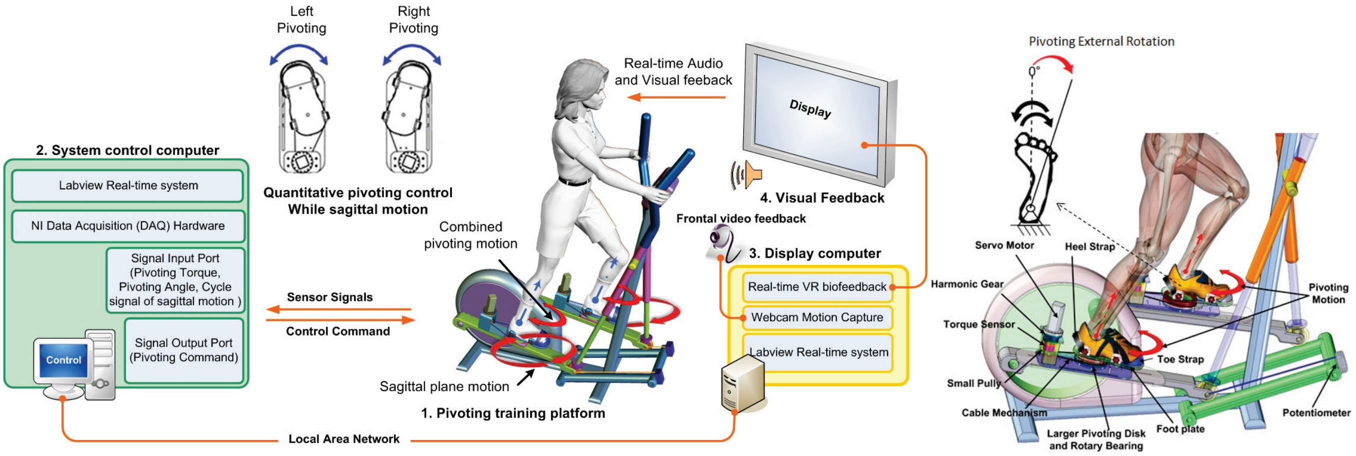

(a) (b)

Fig. 1. (a) Schematics of the pivoting elliptical training system. When the subject was on the pivoting elliptical trainer, the left and right footplate rotations about the tibial long axis were controlled separately or simultaneously by the servomotor control system. Various stimuli such as perturbation and slippery footplate were applied to the subject's feet. The subject received real-time audio and visual feedback of the pivoting movement of the lower limbs and visual feedback of the lower-limb alignments in the frontal plane (e.g. valgus/varus) through a video camera on the front. (b) Schematics of the pivoting mechanisms of the elliptical training system. Each footplate had a pivoting mechanism including a cable-driven transmission mechanism with a footplate, a pivoting disk, a servomotor and a torque sensor, and a schematic diagram of pivoting movements of the foot with indicating 0° position as second toe forward position.

neuromechanical properties was demonstrated through experiments on healthy individuals. Partial works were previously presented in conferences [8-11]. This paper brings more ideas and emphasizes on the detailed system control models and algorithms which have been used in previous preliminary study in conferences paper. All the control method have been further tested and improved, and we are working on more training study with larger sample size and updated training control strategy.

II. METHODS

A. Pivoting Elliptical Training System

The pivoting elliptical training system (PETS) was developed to conduct training on pivoting neuromuscular control of the lower limb during stepping movements and evaluate outcome quantitatively. The conventional footplates on the elliptical trainer were replaced with custom developed pivoting control mechanisms [10, 11] so that subjects stood on the PETS with the second toe pointing forward and the tibial long axis of the subjects aligned with the pivoting axis on the footplate (Fig. 1). The subject's shoe was fixed onto the footplate through toe and heel straps so that the subjects' foot and footplate rotated together.

For controlled pivoting movements of the PETS, a brushless DC servomotor (SA01-100W/48V, Mecapion, Korea) with an built-in encoder (2048 pulse/rev) was used to drive a two-stage of transmission on each side: a precision Harmonic drive gear (50:1, CSF-14, Harmonic Drive^{TM}) mounted to the motor shaft and a cable-driven transmission (speed reduction ratio 2:1) attached underneath the footplate (Fig. 1 (b)). The cable-driven transmission mechanism allowed low friction and enhanced backdrivability of the footplates [10, 12]. The cable-driven mechanism included a pair of cables to transmit clockwise and counter clockwise toque. One end of the cables was fixed onto the small pulley, and the other end was fastened to a larger pivoting disk underneath the footplate. The output torque and speed of the pivoting mechanism was 30 Nm and 180° /sec, respectively. Underneath each servomotor, a torque sensor (56.4 Nm Transducer Techniques, Inc) was mounted between the Harmonic Drive gear and the small pulley of the cable-driven mechanism for measuring the pivoting torque (Fig. 1 (b)).

A linear potentiometer (SP1-50 String Pot, Celesco, USA) was used to determine the stepping cycle. The potentiometer cable was connected to a wheel sliding along the ramp of the PETS and potentiometer body was fixed to the ramp. 0% of the stepping cycle was defined as the highest position of the wheel on the ramp (Fig 1 (b)), and a full cycle corresponded to a full stepping cycle.

The pivoting mechanism was servo-controlled at 1000 Hz sampling rate with various pivoting training modes and quantitative outcome measures done flexibly. Training intensity including amount of internal and/or external pivoting movements and assistive or resistive amplitudes and duration of each task could be adjusted through a user-interface (Fig. 1(a)). To motivate individuals for more effective training [3], real-time audio and visual biofeedback based on the endpoint kinematics (i.e. foot position) were implemented in the display computer (Fig. 1 (a)). The biofeedback signals were transferred via local area network from the system control computer to the display computer at 100 Hz (Fig. 1 (a)). A video camera was used to help the subject track and adjust frontal lower limb alignment during pivoting and stepping.

B. Different Training Modes and Control Algorithms

Three different training modes were developed for injury prevention and rehabilitation using custom control algorithms. The three training modes were spring mode, free mode, and perturbation mode. The PETS was also used to evaluate lower-limb neuromechanical properties. In evaluations, the subject was asked to hold the handlebars of the PETS to control the influence of upper limbs on lower limb performance.

The footplate could be locked at a selected position by a mechanical brake of the servomotor so that PETS functioned as a conventional elliptical trainer. For those who were not ready to start challenging pivoting training due to muscle weakness and instability of their lower limb(s), this mode was used as an initial transition task. For those who were able to run with challenging pivoting tasks, this mode functioned as warming up and cooling down tasks prior to starting or ending the pivoting training.

1) Spring Mode: In this mode, the footplate behaved like a torsional spring while subject's foot moving in the internal and external pivoting directions using (1) [13]:

$$\tau_m = K_{sp}\Delta\theta \quad (1)$$

where τ_m denotes the desired motor command torque, K_{sp} is the defined torsional stiffness, and $\Delta\theta$ is the joint off-axis angular displacement between the current foot pivoting angle and the initial pivoting angle. The level of pivoting rigidity was adjusted with different stiffness gain K_{sp}. When the subject was on PETS, different K_{sp} caused different motorized reaction torsional force and the subject sensed different stabilization assistance from the footplate. If needed, the gain K_{sp} could be adjusted through the user-interface in the system control computer. When K_{sp} was reduced, less stabilization assistance was applied and the pivoting task became harder so that the subject was forced to do more on pivoting neuromuscular control under reduced stabilization assistance. Moreover, different endpoint kinematic targets (e.g. foot angle) showing as biofeedback on the screen (Fig. 1(a)) allowed the subject to conduct not only assistive tasks but also resistive tasks. For example, if the subjects were asked to maintain an initial standing posture (e.g. second toe pointing forward) with certain spring force assistance, the task was easy. However, if the subject was asked to reach a certain internal pivoting position against spring resistance, the task became more difficult since the subjects needed to overcome the spring resistance created by the stiffness control in order to maintain the target position.

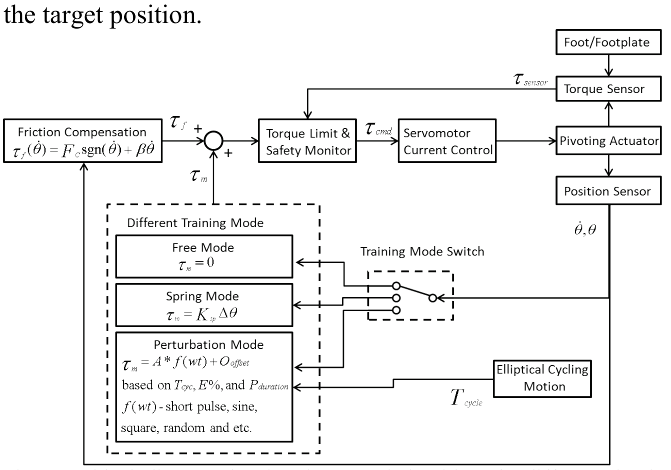

Fig. 2. A block diagram showing the control algorithms for different pivoting training modes. τ_{sensor} denotes the measured pivoting torque applied to the footplate. θ denotes the measured foot or footplate pivoting angle and $\dot{\theta}$ denotes the angular velocity. T_{cyc} denotes cyclic stepping signal from the potentiometer. τ_f denotes friction compensation torque and τ_m denote the desired pivoting torque output based on different pivoting algorithms and control parameters (F_c, β, K_{sp}, T_{cyc} and etc.). τ_{cmd} denotes a safer pivoting command which is calculated based on the desired τ_f, τ_m and measured τ_{sensor}.

2) Free Mode: In this mode, the footplate was controlled as backdrivable. The subject on PETS felt like walking on the ice. Although the cable-driven transmission was backdrivable, friction in the gear may prevent PETS from being backdrivable. Thus, a classic friction compensation model including the Coulomb friction and the viscous friction torque was used to reduce friction [14]:

$$\tau_f(\dot{\theta}) = F_c \operatorname{sgn}(\dot{\theta}) + \beta\dot{\theta} \quad (2)$$

where $\tau_f(\dot{\theta})$ was the estimated friction compensation torque; $\dot{\theta}$ the relative pivoting velocity; β the viscous friction coefficient; and F_c the Coulomb friction. Once F_c and β were identified, the coulomb and viscous friction torque were estimated based on the amplitude and direction of the angular velocity $\dot{\theta}$ of the footplate. Then, the required motor torque $\tau_f(\dot{\theta})$ to compensate for friction was determined to control the motor and make the pivoting movement of PETS backdrivable. Measured friction torque was reduced using the friction compensation model from 3.0 Nm to less than 1.0 Nm, and the breakaway friction was about 0.25Nm.

3) Perturbation mode: In this mode, the footplate generated different types of torque perturbations (e.g. sinusoidal wave, square wave, white-noise and abrupt pulse). The amplitude (e.g. A in Fig. 3), user-defined period (P), duration of perturbation, and desirable offset (e.g. O in Fig. 3) of the perturbations were adjustable based on specific needs. Especially, an offset was specified the direction of pivoting movements in training so that either tibial internal or external pivoting training was focused on by the subject. Figure 3 demonstrated examples in the perturbation mode. Various torque command τ_m was sent to each servomotor independently or simultaneously (Fig. 2) to generate a desired perturbation torque pattern on the footplate(s) so that different intensities and difficulty levels were produced for the pivoting training. For example, sinusoidal perturbation torque input was used for creating a challenging task. On the other hand, a torque pulse was produced at E% in Fig. 3 based on the stepping position.

C. Safety Consideration of Pivoting Stepping Motion

There was a mechanical safety block underneath each footplate to limit the rotation of the footplate so that pivoting movement occurred within a selected safe range (e.g., ±45°). A stop switch was used to enable/disenable the pivoting motion at the subjects' need. The subject on PETS wore a shoulder harness and, if needed, can step off from the footplates to avoid injury.

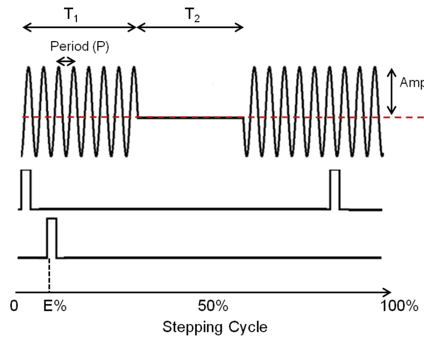

Fig. 3. Different types of torque perturbations during pivoting training combined with sagittal stepping. E% indicates the time when a perturbation pulse occurs, P the period of sinusoidal or other signals, A the amplitude of a torque signal, O the offset value that determined the torque offset applied to the footplate, T_1 the duration of perturbation and T_2 the duration when there was no perturbation.

In addition, the control commands, pivoting angle and torque were monitored and adjusted through the user interface to ensure safer training so that the individual learned to control pivoting movements on PETS and keep proper frontal plane alignment through visual feedback of the video camera. During training, the amplitude of perturbation (e.g. A in Fig. 3) applied to the footplate(s) started from a moderate level and gradually increased to more difficult level and the individual was encouraged to exercise at a safe and challenging level. If needed, heart rate could be also monitored.

D. Evaluation of Neuromechanical Properties

A unique application of PETS was to evaluate neuromechanical properties including proprioceptive acuity, reaction time, instability, and strength in pivoting using pivoting torque sensors and motor encoders.

1) Proprioceptive acuity

In PETS, proprioception referred to kinesthesia, measuring a threshold for individuals to detect subtle passive motion (speed less than 2.5°/s) [15]. Global proprioception was quantified as the foot pivoting angle when they first perceived slow foot pivoting (1°/s) . Pivoting proprioceptive acuity of each leg was tested in internal and external pivoting directions. The leg position was a weight-bearing position in which subject put all weight on each leg or selected static knee flexion postures on PETS. The subject pushed a hand-held button immediately after they felt the subtle movement and told the pivoting direction and the leg moved. The subject was asked to close the eyes to eliminate visual feedback, and testing environment was quiet to minimize influence from other sensory inputs. PETS had the capability of controlling each servomotor randomly to move either internal or external pivoting directions at a random time, so that individuals could not predict when the subtle pivoting movement occurred, at which direction, and which leg moved. The measurement was based on the angular resolution of PETS (204800 pulses/rev).

2) Reaction time

Reaction time was determined as the time from the onset of the perturbing torque pulse to the onset of torque or muscle activity generated by the subject. The torque pulse intensity and width was adjustable depending on the users' need. Fig. 4 showed an example of using PETS to measure the reaction time, with the torque pulse of 4.5Nm in amplitude and 20ms in pulse width. As seen in Fig. 4, T_0 indicated the onset of the torque pulse and T_1 indicated the onset of muscle activation. The onset of muscle activations was defined as the earliest time when the magnitude of muscle activities was higher than three standard deviation of background muscle activities in the time window from 100ms to 5ms prior to the onset of torque pulse [16]. The reaction time (123 ms for the lateral gastrocnemius) in Fig. 4 provided consistent result with previous findings under weight-bearing conditions [17]. Validity of this method on PETS was checked by physiological limitation of reflexive muscle activation timing. Since reaction time (i.e. latency in this case) for tendon tapping, assessing the simple reflex pathway, was around 50ms, the reaction time should not be earlier than the physiological limit. Reaction time measure was used to investigate neuromuscular response following injuries or training due to torque perturbation.

3) Pivoting Instability

Standard deviation of foot pivoting angles, *pivoting instability*, was used to quantify the ability of controlling pivoting during stepping movements with the footplates rotating [9, 11]. Higher pivoting instability indicated that individuals did not control their leg well in the pivoting directions. For example, if a subject controlled his or her feet on an initial standing posture (e.g. second toe forward) all the time during stepping, the pivoting instability was zero. Similar to proprioception measure, the measurement was based on the angular resolution of PETS (204800 pulses/rev).

4) Muscle Strength

With the pivoting disk locked at the neural foot rotation (second toe forward), maximum voluntary contraction (MVC) in tibial internal and external pivoting directions could be quantified by the PETS. Based on previous studies, MVC of tibial external rotation of healthy individuals was 22.2Nm and MVC of internal rotation was 18.5Nm [18] (the output torque of the pivoting mechanism was about 30Nm).

E. Biofeedback to Guide Foot Pivoting and Lower Limb Postures

Real-time visual feedback of foot pivoting angles (from the encoders) and of frontal lower limb alignment (from the video camera) guided the subject to learn to position their feet properly and maintain proper lower limb postures in the various training modes. In addition to visual feedback, real-time audio feedback was provided from PETS so that the subject was aware about the lower limb postures as well as foot positioning during stepping. Furthermore, virtual reality display of lower limbs was used to guide proper foot positions in the various training modes based on real-time feedback of the foot pivoting angles. The virtual reality system showed desired and actual foot postures in real-time to guide the subject for proper foot positions and lower limb postures.

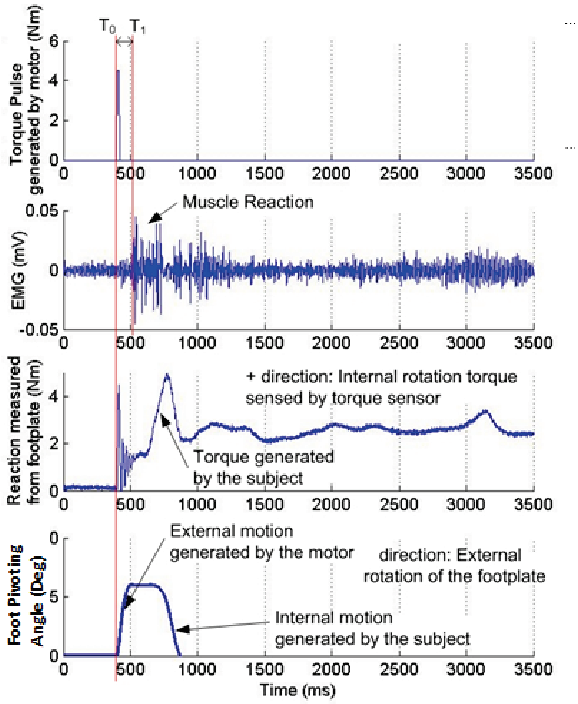

Fig. 4. Evaluation of the reaction time. From top to bottom, the plots correspond to an external torque pulse generated by the servomotor, EMG response of the right lateral gastrocnemius muscle, internal pivoting torque, and external pivoting angle of the footplate, respectively. T_0 indicates the moment when a torque pulse occurred. T_1 indicates the moment when muscle was activated in reaction to the torque pulse. The subject stood on PETS with all weight on the right leg.

III. EXPERIMENTS

Feasibility of the PETS to evaluate and train individuals in pivoting neuromuscular control was investigated on four healthy individuals (Table 1). All healthy individuals did not have history of knee injuries or pain.

TABLE I
SUBJECTS CHARACTERISTICS.

Subject	Gender	Age (year)	Weight (Kg)	Height (Cm)	BMI (kg/m^2)
S1	M	31	70.3	170.2	24.3
S2	M	26	89.4	193	24.0
S3	F	19	56.2	157.5	22.7
S4	F	21	70.3	182.9	21.0

S indicates subject, M indicates male, F indicates female, and BMI indicates body mass index.

A. Alteration of Pivoting Neuromuscular Control in Different Training Modes

Four individuals received a 30-minute training session consisting of fixed modes, spring modes, free modes, and perturbation modes. The perturbation mode used here was a sinusoidal perturbation torque. Offset of the sinusoidal torque and peak of the sinusoidal torque (5-10Nm) were adjusted to individuals' comfortable level to challenge them in the training. The direction of the offset was positive for all individuals so that they focused on internal pivoting directions.

Individuals received each training mode about 4 minutes in the sequence of a free mode, a spring mode, perturbation modes, the spring mode, and the free mode with adequate break between modes to reduce fatigue that could potentially influence on the performance of individuals' ability to control their legs in pivoting directions not due to different training modes. Prior to the first and after the second free mode, individuals were asked to perform about 2 minutes of a fixed mode each. Individuals were asked to maintain their feet at the initial foot rotation (second toe forward) during stepping on PETS and the footplates can rotate in various ways, dependent on the level of difficulty. As shown in Fig. 5, all four individuals were able to control their feet better in the spring mode in comparison to the free mode and the perturbation mode. Specifically, mean pivoting instability during the spring mode was 0.64±0.21° (STD) among four individuals and mean pivoting instability during the free mode was 2.89±0.57° among four individuals. Furthermore, different training modes targeted to work on specific muscles. As seen from Fig. 6, the perturbation mode used 5 Nm offset torque with 2Hz 1.8Nm amplitude sinusoidal pivoting torques in external direction. In this case, this mode allowed individuals working on more internal rotator muscles such as semitendinosus and lateral gastrocnemius muscles in comparison to the fixed mode in order to maintain initial postures during stepping. Furthermore, due to the capability of adjusting a height of PETS, gluteus muscles, quadriceps or calf muscles could be focused at subject-specific needs.

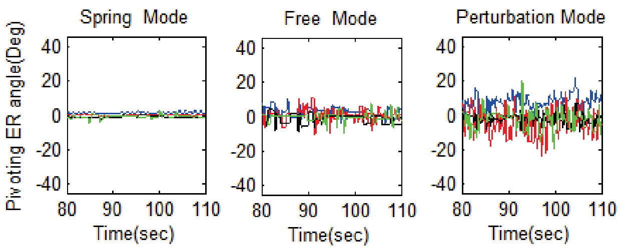

Fig. 5. A typical example of pivoting external (ER) angle in the spring mode, the free mode, and the perturbation mode between 80 to 110 seconds of stepping exercises on the pivoting elliptical system. Each color corresponds to data from each subject, with the difference in pivoting angle reflecting different capability of controlling the lower limb pivoting. The mechanical limits of the pivoting system were ±45°.

B. Modulation of Pivoting Neuromechanical Properties Following Training Sessions

1) Pivoting Instability

To test the feasibility of PETS as a training tool, the same four individuals did multiple 30-minute training sessions. Following eight sessions of training, all individuals reduced pivoting instability considerably, indicating better controlling their lower limb in pivoting in the free mode..

The mean pivoting instability at the pre-evaluation session was 4.16±0.90° and at the post-evaluation session was 1.44±0.27° during the free mode. In addition, the mean pivoting instability at the pre-evaluation session was 6.74±0.48° and at the post-evaluation was 3.68±0.46° during the sinusoidal perturbation mode using 5 Nm offset torque of the external direction with 2Hz 1.8 Nm amplitude sinusoidal pivoting torques.

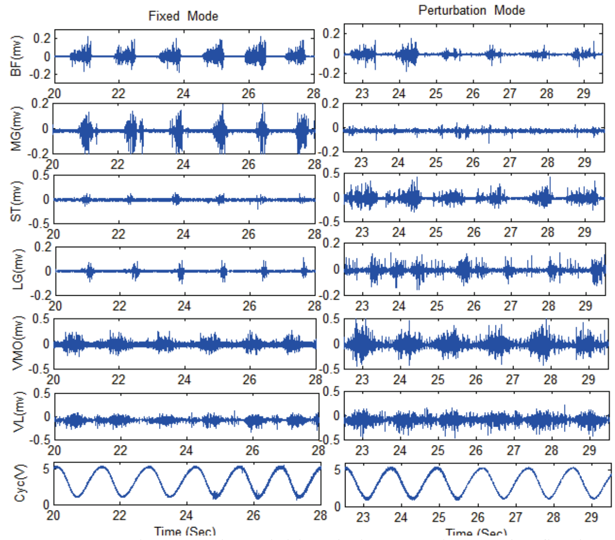

Fig. 6. Representative muscle activities during stepping at the fixed mode (footplates locked, left panel) and the perturbation mode (right panel). BF denotes biceps femoris, MG medial gastrocnemius, ST semitendinosus, LG lateral gastrocnemius, VMO vastus medialis oblique, VL vastus lateralis, Cyc the stepping cycle. The subject used more internal rotator muscles such as ST and LG in the perturbation mode in comparison to the fixed mode.

2) Proprioceptive acuity

In comparison to the pre-evaluation session, individuals in the post-evaluation session showed a pattern of improved proprioceptive acuity in both internal and external pivoting directions under weight bearing. The four individuals closed their eye and pushed the hand-held button immediately after they felt the pivoting movement. Prior to the actual testing, each individual received a session to familiarize the tasks so that proprioception was measured without involving any learning curve of the tasks that could influence on individuals' performance during proprioception tasks. The proprioception in the internal pivoting direction at the pre-evaluation session was 4.08±3.45° and at the post-evaluation session was 1.84±0.83°. The mean value of proprioception in the external pivoting direction at the pre-evaluation session was 3.16±0.85° and at the post-evaluation session was 1.73±0.20°.

3) Reaction time

Reaction time was measured on subject 3 and subject 4 before training and following 8 sessions of training. The task was to react as quickly as possible to move the footplate back to the initial position. There is a trend of quicker muscle response in lateral gastrocnemius muscle following an internal 4.5Nm torque pulse with 20ms pulse width in comparison to the pre- evaluation when each individual put her weight on the right side leg. Subject 3 reduced the reaction time from 101 ms to 80 ms and subject 4 reduced the reaction time from 340 ms to 287 ms.

IV. DISCUSSION AND CONCLUSION

A pivoting elliptical training system was developed to aid clinicians, researchers, and individuals for lower limb injury prevention and rehabilitation. The system is able to 1) evaluate pivoting neuromechanical properties such as pivoting instability, proprioceptive acuity, reaction time and strength, and 2) train pivoting neuromuscular control at subject-specific needs using various levels of training modes from easy to difficult levels. The different controllable modes can provide different stimuli such as feeling like walking on ice, external torque perturbation on feet in either internal or external pivoting directions. In addition to development of the PETS, changes in pivoting neuromuscular control across different training modes and changes of pivoting neuromechanical properties following eight training sessions were demonstrated on four healthy individuals.

In comparison to conventional training or therapy, more effective training targeting subject-specific needs can be realized using PETS that has the capabilities of producing repeatable and high intensities of movements based on subject-specific needs. As a result, individuals can learn to control movements in pivoting directions under functionally relevant and weight-bearing conditions with real-time audio-visual feedback. Effectiveness of training with PETS needs to be further investigated over larger samples. In the long run, PETS can potentially be used as a practical training and evaluation platform to improve injury prevention and post-injury rehabilitation.

DISCLOSURE

Li-Qun Zhang and Yupeng Ren have equity positions in Rehabtek LLC, which is involved in developing the pivoting elliptical trainer in this study.

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