Fatigue Induced Changes in Knee Joint Force, Angular Velocity and Joint Moments During Saggital Perturbations of Single-Leg Stance

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Abstract: The purpose of the current study was to investigate the effect of knee muscle fatigue on knee joint moment, knee joint force and knee angular velocity during sagittal perturbations of single-leg stance. 15 healthy men (age = 26.2±2.1 yr) with no history of knee injury or trauma participated in this study. Fatigue induced to knee muscle using a standard Monark bicycle ergometer. Isokinetic Dynamometer (Chattanooga, TN) was used to measure maximal knee force and time to task failure before and after fatigue protocol. Reflex muscle activity measured during single-leg stance perturbation before and after fatigue protocol. Using a motion capture system and force plate, knee kinematics data and ground reaction force were also recorded before and after fatiguing. Maximal knee force, time to task failure and associated EMG activities were significantly reduced (for both flexion and extension directions) after fatigue (P<0.05). Moreover reflex activity of the knee muscles was significantly lower during post exercise single leg stance perturbation with respect to pre exercise phase (P < 0.05). However knee angular velocity increased (P < 0.05), knee joint force decreased (P< 0.05) and knee joint moment increased in the frontal (P< 0.05) and horizontal plan (P< 0.05) after dynamic fatigue protocol. The result of the current study demonstrated, that fatigue induced changes in muscle activity patterns around knee joint. The altered muscle activity pattern around knee joint can contribute to an increased knee varus moment and an excessive internal rotation of the tibia, during destabilizing perturbation of single-leg stance. This may further increase the risk ACL injuries during single-leg stance cutting action.

Key words: Electromyography %Muscle Fatigue %Single-Leg Stance Pertubation %Knee Kinematics

INTRODUCTION

Dynamic stability of the knee joint depends on the ability of the knee muscles to maintain the structure of the knee joint (...e.g., ligament, patella...) in normal anatomic position during unexpected postural perturbation. Fatigue is an inevitable part of any exercise training that may develop as central and/or peripheral fatigue in human skeletal muscle [1, 2]. Knee muscles are more susceptible to fatigue due to frequent eccentric loading of the leg during sport and daily activities. After fatiguing activity, a high accumulation of metabolites (acid lactate...) within the skeletal muscle [3], induce motor control changes at the level of muscle fiber membrane and/or central nerve system [1, 4] which in turn may contribute to changes in muscle activity pattern around knee joint [5]. In fact, maintaining dynamic stability during unexpected perturbation is dependent on cortically programmed muscle activations and reflex-supplied muscle contractions [6]. Single-leg landing is a common technique in sports [7]. Single-leg stance has been reported as major risk of knee injuries. During normal stance (stance on two feet) quadriceps femoris and hamstrings muscles compress both the lateral and medial compartments of the knee joint, thereby preventing the dominant adduction moment in the frontal plane [8-10]. However, in single-leg stance position, where genu varus alignment is dominant, the ability of knee muscles would reduce to control dynamic knee stability and as consequence may increase knee joint moments in the frontal plan [11-13]. Moreover, it has been reported that changes in knee angular velocity and joint force, were positively correlated with changes in knee joint moment [13]. In the current study, it has been

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hypothesized that fatigue induces motor control changes, would probably contribute to changes in knee angular velocity and joint force and may further increase knee joint moment in the frontal plane during postural perturbation. Therefore the purpose of the current study was to investigate the effect of knee muscle fatigue on knee kinematics during sagittal perturbations of single-leg stance.

MATERIAL AND METHODS

Experimental Design and Approach: Using a force plate and video camera system kinetic and kinematic signals [14], were recorded during destabilizing perturbation of single-leg stance before and after dynamic fatiguing exercise. Moreover, surface EMG signals were simultaneously recorded from knee muscles during destabilizing perturbation of single-leg stance.

Subjects: 15 healthy men (mean±SD; age = 26.2±2.1 yr, body mass = 78.5±6.4 kg, height = 1.76±0.08 m) with no history of knee injury or trauma participated in the study. All subjects were right leg dominant and were not involved in regular exercise of their knee extensor muscles for at least 6 months before the experiment.

Fatigue Protocol: Using a standard Monark bicycle ergometer fatigue induced to knee muscle. Subjects were asked to maintain a cadence of 70 RPM at a work rate of 80-110 W throughout the fatigue protocol. The work rate was increased by 20W every minute until volitional exhaustion.

Muscle Function and Electromyography: Surface EMG signals were recorded from knee extensors (vastus lateralis, rectus femoris and vastus medialis) and knee flexors (medial and lateral heads of he hamstring and the medial and lateral heads of gastrocnemius) of the right limb by circular Ag–AgCl surface electrodes (Ambu Neuroline, conductive area 28 mm²) during maximal knee force and submaximal sustained contraction. Surface EMG electrodes were placed in bipolar configuration at 15% of the distance between medial border (VM), superior border (RF) and lateral border (VL), of the patella and anterior superior iliac spine (ASIS). For knee flexors, the electrodes were placed on the most distal portion of the medial and lateral belly of the hamstring and medial and lateral head of gastrocnemius. The subject performed three maximal knee extension and flexion on the KinCom Isokinetic Dynamometer (Chattanooga, TN) with the hip and knee in 90 deg- flexion. The highest MVC value was used as a reference for the definition of the submaximal force level. Subjects performed submaximal isometric knee extension and flexion at 50% MVC, which was sustained until task failure. Task failure was defined as a drop in force greater than 5% MVC for more than 5 s after strong verbal encouragement to the subject to maintain the target force.

Perturbation Protocol and Electromyography: Immediately after fatigue protocol, subjects stood with their right limb on a movable platform and their left limb ground off. A positioning actuator translated the platform 6 cm frontally (sagittal plan) in 250ms. Four 3-second trials were collected. Subjects were unaware of when the plate would be triggered to move. The onset of plate movement was accompanied by a trigger, used as reference to analyze changes in knee reflex and knee kinematics. Surface EMG was recorded from knee extensors and flexors as described in previous section.

Perturbation Protocol and Kinematic: Eleven reflective markers were placed on the subject's body (right and left anterior superior iliac spines, right greater trochanter, lateral and medial femoral epicondyls, lateral and medial malleolus, shank, calcaneous and the distal end of the first and fifth metatarsal) as presented in Figure 1. Kinematic data were measured using a motion capture system (Vicon, Oxford Metrics, Inc.) and ground reaction force data were measured at 2048 Hz using an AMTI force platforms (AMTI, Watertown, MA, USA) during single-leg stance perturbation.

Data Analysis

Electromyography: Surface EMG signals were amplified (EMG amplifier, EMG-128, LISiN-OT Bioelettronica, Torino, Italy, bandwidth 10–500 Hz), sampled at 2048 Hz, low pass filtered and stored after 12-bit A/D conversion. Average rectified value (ARV) was estimated from the EMG signals for 1-s-long epochs during maximal contraction and 1-s-long epochs were averaged in intervals of 10% of the time to task failure for sustained contraction. To assess muscle reflex activity, the ARV of individual muscles was calculated over a fixed window, which was 175-msec after the onset of plate movement (monosynaptic stretch reflex) (15).
Fig. 1: A sample of surface EMG signals recorded from distal portion of VM, RF and VL during single-leg stance perturbation performed A) before and B) after muscle fatigue.

Fig. 2: Schematic representation of marker positions on the right and left anterior superior iliac spines (ASIS), greater trochanter, lateral and medial femoral epicondyls, lateral and medial malleolus, shank, calcaneous and the distal end of the first and fifth metatarsal (A) and the absolute orthogonal reference system; X axis is along the walkway, the Z axis is the vertical pointing upwards and the Y axis is perpendicular to both X and Z directions. (B).

**Kinematic:** An inverse dynamics method applied to compute the intersegment joint force, knee angular velocity and moments using Visual3D (C-Motion, Inc.), which was expressed in the local orthogonal femoral frame. According to the relative Euler angles a set of orthogonal embedded axes both in the moving segment as well as in the reference segment is necessary to calculate body kinematics. In the absolute orthogonal reference X axis is along the walkway, the Z axis is the vertical pointing upwards and the Y axis is perpendicular to both X and Z directions, forming a right-handed Cartesian coordinate system (Figure 2). For the shank segment, the references are thigh-embedded axes. All raw coordinate data were smoothed using a fourth-order Butterworth low-pass filter (cut off frequency 7 Hz). All kinematic and kinetic data were analyzed after the onset of plate movement. Kinematic and kinetic data were normalized to body weight and height.
Fig. 3: Average knee joint moment (Subjects, N= 15) in frontal (A) and horizontal plan (B); and knee joint force (C) and knee joint angular velocity (D) computed before (solid line) and after muscle fatigue (dashed line).

**Statistical Analysis:** One way measure ANOVA applied to evaluate time task failure, maximal knee forces and associated EMG changes during knee flexion and extension before and after fatigue protocol. One way measure ANOVA used to measure change in reflex activity of the knee muscles during single leg stance perturbation performed before and after dynamic fatiguing exercise. One way measure ANOVA also applied to assess knee angular velocity (knee angular velocity × condition) knee joint force (knee joint force × condition) and knee joint moment (knee joint moment × condition) during single leg stance perturbation before and after dynamic fatiguing exercise.

**RESULTS**

One way measure ANOVA revealed that, time to task failure, maximal knee forces and associated EMG changes (for both flexion and extension knee contraction) were significantly reduced after fatiguing exercise (P< 0.05). Moreover, reflex activity of the knee muscles was significantly lower during post exercise single leg stance perturbation with respect to pre exercise phase (F = 4.7, P < 0.05). However knee angular velocity increased (F= 3.5, P < 0.05), knee joint force decreased (F= 2.8, P< 0.05) and knee joint moment increased in the frontal (6.1, P< 0.05) and horizontal plan (F= 5.6, P< 0.05) after dynamic fatigue protocol (Figure 2).

**DISCUSSION**

This study demonstrated larger knee joint moment in the frontal and horizontal plans, higher knee angular velocity and lower knee joint force during destabilizing perturbation of the single-leg stance after muscle fatigue. Moreover, reflex muscle activities around knee joint were significantly reduced after fatiguing exercise. Results suggested that muscle fatigue contribute to a reduced ability of the knee muscles to stabilize the knee joint during a destabilizing event and as consequence can increase knee varus moments in the frontal plan. The increased knee varus moments has been reported as major risk factor of knee injuries.
Maximal voluntary contraction and time to task failure for the fatigued knee muscles were significantly ($p<0.05$) decreased after dynamic ergometer exercise, which is in agreement with previous studies [16, 17]. A significant ($p<0.05$) reduction in maximal voluntary contraction and time to task failure after dynamic ergometer exercise may be related to a failure in signal transmission in excitation-contraction coupling pathways (EC), most likely due to metabolic accumulation [18]. Moreover, metabolic accumulation can reduce myofibrillar ATPase activity, which would likely decrease the detachment rate of cross bridges and muscle contraction [19]. Meanwhile, a greater decrease in EMG amplitude was also observed during the post fatigue sustained contraction, indicating that metabolic accumulations inhibit neural system to increase motor unit recruitment and/or motor unit discharge rate required to compensate for contractile failure caused by fatigue [16, 18].

After dynamic ergometer exercise, reflex activity of knee muscles decreased during the destabilizing perturbations of single-leg stance, as compared with pre-fatigue condition. The decreased reflex muscle activation after fatiguing dynamic exercise can be explained by a disturbance in the Ia-motoneuron system involved in regulating muscle activation. Fatigue changes the function of intrasensory chain and static bag fibers [20] and consequently, results in a reduction in Ia afferent inflow from muscle spindles [21]. Fatigue would also effect on force-feedback mediated by the Golgi tendon organ and therefore can inhibit spinal motor neurons [22]. After fatiguing exercise, a high accumulation of metabolites would also changes muscle fiber membrane properties, which in turn, result in a decreased muscle fiber conduction velocity along muscle fibers and contribute reducing muscle contraction. This result indicated that the level of coactivation between the knee extensors and flexors is altered after fatiguing exercise, which most probably results in joint instability or laxity, imposing an abnormal load on the structures of the knee, thus leaving them more susceptible to injury.

After fatiguing dynamic exercise, a significant increase in knee angular velocity and a reduction in knee joint force observed during the destabilizing perturbations of single-leg stance. However, changes in knee angular velocity and knee joint force was accompanied with a significant increase in knee joint moments in the frontal and horizontal plans. A significant reduction in knee joint force, indicate that the ability of the quadriceps femoris and hamstrings muscles are reduced to compress both the lateral and medial compartments of the knee joint [8, 9]. An increase in knee angular velocity also reflects an insufficient stiffness of the quadriceps muscles, to control eccentric contraction (extensor torques developed during loaded knee flexion), was required to decelerate the knee to prevent buckling during perturbation [23]. These changes in knee kinematics impose the dominant abduction moment in the frontal plane and increase internal rotation of the tibia in the horizontal plane during single-leg stance [13]. An increased abduction/varus moment accompany with the internal rotation of the tibia during single-leg stance maneuver, may expose knee joint structures such as anterior cruciate ligament (ACL) to abnormal loading [8]. Previous studies reported that, knee kinematic changes associated with single-leg stance cutting action act as potential mechanism of non-contact ACL injury [24]. For example, majority of non-contact ACL injuries occur during sports in which the players are involved in some form of pivoting and single-leg stance cutting action [25-27]. Axial rotation (horizontal plane) and/or excessive internal rotation of the tibia with respect to femur during single-leg stance maneuver has been suggested as major factor of ACL injuries [28, 29]. According to the previous studies, tibial rotation occurring during single-leg stance maneuver is likely to be of a large enough magnitude to produce external axial load within the ACL, leading rupture of the ligament substance. As discussed above, previous studies demonstrated that single-leg stance cutting actions, yields dominated varus moment and an excessive internal rotation of the tibia, potentially exposing ACL to abnormal loading [11, 12]. Therefore fatigue induce changes in knee muscle activities, can further increase varus moment and/or internal rotation of the tibia during destabilizing perturbation of single-stance and may further contribute to ACL injuries. These results may partly explain that, why ACL injuries is common after long term fatiguing exercise, in which individuals are involved in single-leg stance cutting action [25-27].

**CONCLUSION**

The result of the current study demonstrated, that fatigue induces changes in muscle activity patterns around knee joint, can contribute to an increased knee varus moment and an excessive internal rotation of the tibia, during destabilizing perturbation of single-leg stance. This may further increase the risk ACL injuries during single-leg stance cutting action.
REFERENCES


