CONTRIBUTION OF LOWER LIMB EXTENSORS AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION DURING JOGGING AND HOPPING

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1. Abstract

Background: Anterior cruciate ligament (ACL) rupture is one of the most common knee injuries in sports such as football and basketball. The role of the ACL is to limit the excessive anterior tibial translation as well as axial tibial and valgus knee rotations. ***Purpose:*** The purpose of this study was to estimate the percentage contribution of hip extensors, knee extensors and ankle plantar flexors after ACL reconstruction during two of the most common functional activities in sports which are jogging and hopping. ***Subjects and Method:*** This study was conducted on patients with semitendinosus ACL reconstruction during jogging and single leg forward hopping for a predetermined distance. Twenty patients (19 males and 1 female) were consented to participate in this study. Mean (±SD) age, weight and height were 24.8 (±5.1) years, 75.6 (±7.08) kg, and 1.76 (±0.03) m respectively. Patients were included in the study if they had a unilateral single bundle semitendinosus ACL reconstruction that was performed from six to 12 months prior to data collection. The captured data were analyzed by the 3D Qualysis system for gait analysis. The measured variables were the hip, knee and ankle extension moments (Nm/Kg) at the instant of the loading response of the foot on the force platform during jogging and during single leg forward hopping after fatigue. ***Results and discussion*:** The statistical analysis using SPSS program revealed that the highest percentage contribution of the lower limb extensors was reported from knee extensors (43.13%) followed by the ankle plantar flexors (37.26%) and then hip extensors (19.61%) during hopping. The sequence of contribution (knee, ankle and hip) was similar in the involved and non-involved limb. While in jogging activities, the moments generated from the ankle plantar flexors was the highest (41.3%) followed by knee (33.79%) and hip extension moments (24.89%). This means that the extension moments generated from knee extensors to compensate for reconstructed ACL was higher than the extensor moments in both hip and ankle joint in hopping activities. This is because the mechanism of hopping requires higher shock absorbing capacity from the knee joint than jogging. On the other hand, during jogging, ankle plantar flexors' moments were higher than hip and knee as the mechanism of jogging resembles fast walking activities. ***Conclusion:*** Rehabilitation program of reconstructed ACL should emphasize on knee extension moments followed by ankle and hip in sport activities requiring much hopping. On the other hand, if the sport activities require more jogging, the sequence of training program is better to be for plantar flexors then knee and hip extensors.

Keywords*:* *ACL, Reconstruction, Fatigue, Extension moments.*

2. INTRODUCTION

Anterior cruciate ligament (ACL) rupture is one of the most common knee injuries in sports. Because of its key function as the primary restraint against anterior tibial translation, ACL disruption causes alterations in knee kinematics which are most likely to result in secondary degenerative changes and long-term functional impairment (Dargel et al. 2007). Numerous studies have found females to possess a higher rate of non-contact anterior cruciate ligament injury compared to males during athletic competition (Borotikar et al., 2008; Decker et al., 2003). The role of the ACL is to limit the excessive anterior tibial translation as well as axial tibial and valgus knee rotations (Amis et al., 2005; Demorat et al., 2004; Herrington and Fowler, 2006; Logan et al., 2004; Woo et al., 2006). Adaptation to ACL deficiency includes increased hamstring activity to maintain stability and to provide anterior tibial restraint, and diminished quadriceps activity to reduce the demand on the anterior cruciate ligament (Thambyah et al., 2004).

The primary clinical goals of ACL reconstruction surgery are to restore stability and regain the lost functions due to ACL injury. The reconstructive surgery is generally considered successful if anterior tibial translation in the reconstructed knee is similar to that of the uninjured knee and the patient is eventually able to resume a preinjury activity level (Tashman et al., 2004; Woo et al., 2006). ACL reconstruction is estimated to decrease the potentiality for degenerative changes in the long term due to the reduction in the abnormal shear forces (Ruiz et al., 2002). Factors that determine the fate of an ACL reconstruction include graft selection, tunnel placement, initial graft tension, graft fixation, graft tunnel motion and rate of graft healing. The most common autografts used for ACL reconstruction are the patellar tendon and hamstrings tendons (Adam et al., 2004; Woo et al., 2006). The researchers have studied the lower limb kinetics and kinematics and active muscle control during functional activities as walking, single–limb landing and sidestep cutting maneuvers after hamstring and patellar tendon ACL reconstruction (Nagano et al., 2009; Thambyah et al., 2004).

The previous studies on patients with ACL reconstruction suggested that the hip or ankle extensors may compensate for the knee extension moment deficit. The researchers suggested that functional testing should be performed both under non-fatigue and fatigue conditions, to accomplish comprehensive evaluation of lower extremity function after ACL reconstruction (Augustsson et al., 2004). The effect of fatigue on the lower limb kinetics, kinematics and active muscle control during functional activities as walking, single–limb landing and sidestep cutting maneuvers after ACL reconstruction have been studied by several authors, some reported non significant change after fatigue (Sanna and O'Connor, 2008), others found significant change in these parameters during and after fatigue (Borotikar et al., 2008; Gehring et al., 2009; Madigan and Pidcoe, 2003). However, few studies investigated these parameters during a more demanding functional activities as jogging and single leg forward hopping.

This study investigated the percentage of contribution of lower limb extensors in performing the functions after fatigue. This study was conducted on patients with semitendinosus ACL reconstruction during jogging and single leg forward hopping for a predetermined distance. The statistical hypothesis of the study is stated that there is no significant difference in the percentage of moment contribution between hip extensors, knee extensors and ankle plantar flexors in patients with ACL reconstruction whether in jogging or single leg forward hopping in the involved or non involved limb.

3. METHODS

Subjects

Twenty patients (19 males and 1 female) were referred by one orthopedic surgeon and they were consented to participate in this study. Mean (±SD) age, weight and height were 24.8 (±5.1) years, 75.6 (±7.08) kg, and 1.76 (±0.03) m respectively. Patients were included in the study if they had a unilateral single bundle semitendinosus ACL reconstruction that was performed from six to 12 months prior to data collection. They followed similar rehabilitation programs and the operated extremities scored at least 85% of the distance covered by the sound side in the horizontal single leg hop distance test and scored at least 85% of the score of non-operated sides in the Lysholm knee scoring scale.

Instrumentation

The concerned kinetic variables, the hip, knee and ankle extension moments and their summation in the term of support moments, were measured by a 3D motion analysis system (Qualysis, Inc, Gothenburg, Sweden). This system consists of a motion capture unit (six infrared high speed optical ProReflex cameras), an AMTI force plate (Advanced Mechanical Technology Inc., USA) with sampling rate 1200 Hz (figure 1, a and b), twenty passive reflective markers attached to the subject's body, calibration unit, and a personal computer with its accompanying software.


(a)


(b)

Figure (1): 3D motion analysis system with its (a):6 ProReflex infrared cameras, and (b) AMTI force platform

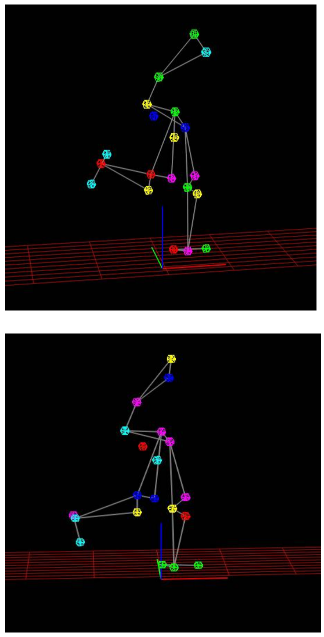
Procedure

After checking out the inclusion criteria and the Lysholm score, three trials of maximum single leg hop test were performed for the operated and non-operated limbs. The mean of the three trials was calculated for each limb. A 50% of the mean maximum single leg hop distance of the sound side was calculated and determined to be the sites of location of floor landmarks. At the level of these landmarks, the patients performed the hopping and jogging activities. Each patient performed practice trials to be familiar with the required tasks.

Each patient underwent a general fatigue exercises in the form of six minutes walk test and three cycles of ascending and descending 72 stairs which incorporates three floors. Then the twenty passive reflective markers were attached to the following bony landmarks; acromion processes, 12th thoracic vertebral spinous process, second sacral vertebra, anterior superior iliac spines, greater trochanters, superior borders of patellae, inferior to the lateral aspect of the lateral femoral condyles (knee joint line), tibial tuberosities, lateral malleoli, posterior aspect of the calcaneus, and on the dorsum of the feet between the second and third metatarsal bones.

Then lower extremity fatigue was induced by repetitive single leg mini squats, fatigue was reached when the squats were no longer possible. This local fatigue exercise was started with the non-operated extremity followed by capturing the data of that limb during jogging (figure 2 a) and single leg forward hopping at the predetermined distance (figure 2 b). This sequence was repeated for the operated limb. Three testing trials were captured for the jogging task and another three for hopping one. The single-leg squats is used to induce neuromuscular fatigue because it is a closed kinetic chain movement that typically involves multiple muscle groups including the hip extensors, knee extensors and ankle planter flexors (Borotikar, et al., 2008).

The captured data were analyzed by the Qualysis system software. The measured variables were the hip, knee and ankle extension moments (in Nm/kg) (figure 3) at the instant of the loading response of the foot on the force platform during jogging and during single leg forward hopping for a predetermined distance in addition to the total support moment.



(a) (b)

Figure (2): The captured data of the patients while performing (a) hopping, and (b) jogging and the foot contacted the force platform. *(Adopted from the Qualysis system software*

(a) (b) (c)

Figure (3): Moments generated from (a) hip extensors, (b) knee extensors and (c) ankle plantar flexors at the instant of loading response of the foot at the force platform. *(Adopted from the Qualysis system software)*

Data Analysis

Data were analyzed using SPSS program to find out the contribution of each muscle group (hip extensors, knee extensors and ankle plantar flexors) on the total extension moment of the lower extremity for both the involved and non involved limbs during jogging and hopping. The percentage contribution of each muscle group moment was calculated by the following equation:

$$\text{\% of hip extension moment} = \frac{\text{recorded hip extension moment}}{\text{total lower limb extension moment}} \times 100$$

4. RESULTS

a) Contribution of lower limb extension moments during jogging

The mean value of hip extension moment (HEM) of the involved limb (IL) during jogging was 1.03 ± 0.47 Nm/kg, and its mean percentage contribution value was 24.89±9.68% from the total score (4.11 Nm/kg). While the mean value of the non-involved lower limb (NIL) was 0.96±0.40 Nm/kg and its mean percentage contribution was 21.19±6.756 % from the total score (4.47 Nm/kg) as indicated in table (1). From the table it is obvious that during jogging activities, the contribution of the moment generated from the ankle plantar flexors "AEM" (41.3%) was the highest followed by knee extension moment "KEM" (33.79%) and then HEM (24.89%) in the involved limb (ACL reconstructed limb). Similarly, for the noninvolved limb, the highest percentage contribution of the lower limb moment was reported from the ankle plantar flexors (40.24%) followed by the knee extensors (38.56%) and hip extensors (21.19%). Statistical analysis using paired t test between the involved and non involved limb revealed that there was no significant difference between both limbs in terms of the moments generated and their percentage contributions. Figure (4) illustrated the previous results.

Table (1): Lower limb (hip, knee and ankle) extension moments and their percentages contribution to the total moment during jogging after fatigue in ACL reconstructed patients.

	Lower Limb Extension Moments													
	HEM		KEM		AEM		Total		%HEM		%KEM		%AEM	
	X±SD	SEM	X±SD	SEM	X±SD	SEM	X±SD	SEM	X±SD	SEM	X±SD	SEM	X±SD	SEM
IL	1.03 ±0.47	0.12	1.402 ±0.593	0.15	1.678 ±0.364	0.091	4.11 ±0.71	0.17	24.89 ±9.68	2.42	33.79 ±12.8	3.2	41.3 ±8.44	2.1
NIL	0.96 ±0.4	0.1	1.80 ±0.98	0.25	1.718 ±0.49	0.124	4.47 ±0.87	0.21	21.19 ±6.76	1.68	38.56 ±14.24	3.56	40.24 ±13.62	3.41
t-test	0.47		1.63		0.468		1.3		1.25		0.66		1.38	
p-value	0.64		0.11		0.64		0.2		0.21		0.51		0.18	
Sig.	NS		NS		NS		NS		NS		NS		NS	

X±SD: Mean ± Standard Deviation, SEM: Standard Error of Mean, IL: (Involved limb), NIL: (non involved limb), Sig: (Significance level), NS: non significant

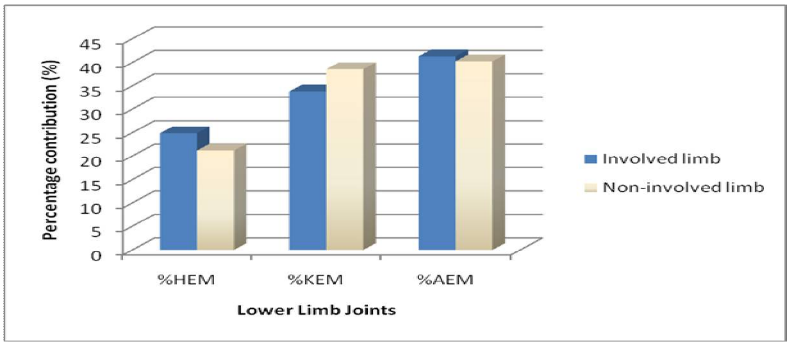


Figure (4): Percentage contribution of hip, knee and ankle extension moments in relation to the total generated moment in patients with reconstructed ACL during jogging after fatigue.

b) Contribution of lower limb extension moments during hopping

During hopping the statistical analysis of the results of the hip, knee and ankle extension moments and their percentages contribution from the total moment during hopping indicated that the highest percentage contribution of the limb moment was recorded from the knee joint (43.13%) followed by the ankle joint (37.26%) and then the hip joint (19.61%) in the involved limb. For the non involved limb the sequence of contribution was the same with different percentages which were knee (47.69%), ankle (26.44%) and hip (25.87%). Non statistically significant differences were reported between the involved and non involved limb regarding the mean values of the moments and their percentage contribution except for the percentage contribution of the ankle plantar flexors where the involved limb produced statistically higher percentage contribution than the non involved limb ($p<0.05$). All the recoded values and percentages with their corresponding figure are presented in table (2) and figure (5).

Table (2): Lower limb (hip, knee and ankle) extension moments and their percentages contribution to the total moment during hopping after fatigue in ACL reconstructed patients.

	Lower Limb Extension Moments													
	HEM		KEM		AEM		Total		%HEM		%KEM		%AEM	
	X±SD	SEM	X±SD	SEM	X±SD	SEM	X±SD	SEM	X±SD	SEM	X±SD	SEM	X±SD	SEM
IL	0.9 ±0.73	0.18	1.63 ±0.48	0.12	1.56 ±0.49	0.21	4.09 ±1.41	0.35	19.61 ±10.94	2.74	43.13 ±15.47	3.86	37.26 ±15.79	3.95
NIL	1.28 ±0.87	0.22	2.02 ±0.61	0.15	1.26 ±0.69	0.17	4.56 ±0.99	0.25	25.87 ±15.81	3.95	47.69 ±19.98	4.99	26.44 ±10.17	2.67
t-test	1.34		2.02		1.08		1.109		1.302		0.72		2.26	
p-value	0.18		0.05		0.28		0.27		0.2		0.47		0.03	
Sig.	NS		S		NS		NS		NS		NS		S	

IL: (Involved limb), NIL: (non involved limb), Sig: (Significance level), NS: non significant, S: Significant

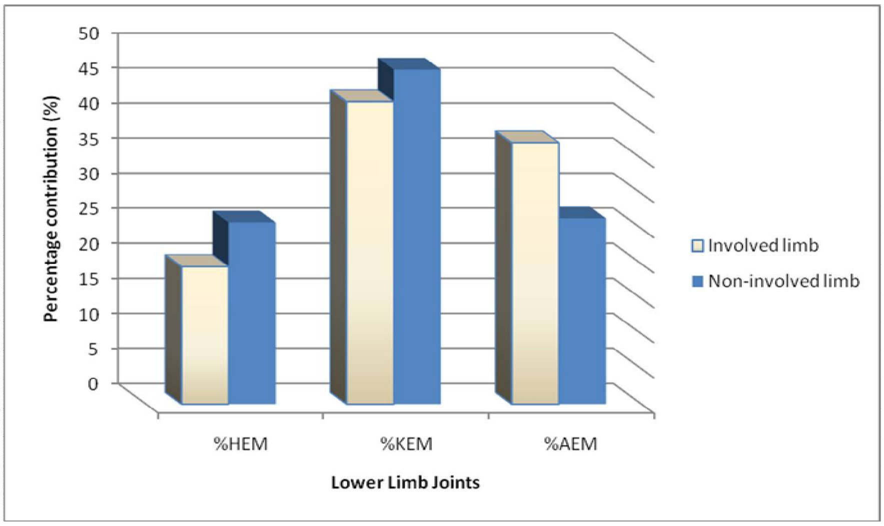


Figure (5): Percentage contribution of hip, knee and ankle extension moments in relation to the total generated moment in patients with reconstructed ACL during hopping after fatigue.

5. DISCUSSION:

Changes in the lower extremity strength following ACL reconstruction has been recorded in every muscle group of the lower limb. Karanikas et al., (2004) reported strength loss in both knee extensors and knee flexors in all patients who had undergone reconstruction surgery after the same ACL rehabilitation program. The results of the current study revealed that during jogging, the highest percentage contribution of the total moment generated by the lower limb extensors was reported from the ankle plantar flexors (41.3%). The next contribution was from the knee extensors (33.79 %) and the lowest contribution to the total moment was generated from the hip extensors (24.89%). This sequence of percentage contribution may be attributed to the fact that jogging resembles fast walking activity. During normal walking the plantar flexor moment is higher than knee extension moment and hip extension moment. This relationship between the three lower limb moments indicates that as the body weight transfers from above downward, higher demand from the supporting moment is required to compensate for the reconstructed ACL. The same sequence of contribution was found for the injured and non injured limbs.

The previous relationship is also supported by the study of Shimokochi et al (2009). The authors evaluated the relationship between knee extensor moment with ankle planterflexor and hip extensor moments, and the relationship between knee extensor moment and the center of pressure location, as a neuromuscular indicator of the center of mass position. The study was performed on 18 healthy active women. Data were collected during single-leg landing by the dominant leg from a 45-cm box. The results suggested that a lower knee extensor moment was related to high ankle planterflexor and hip extensor moments. Moreover it was found that leaning the body forward during single leg landing shifted the center of mass anteriorly, which increased the hamstring and planterflexor muscles demands and reduced the quadriceps muscle demands. This study is limited by inability to generalize the findings on other landing tasks or other populations as the tasks were performed with bare feet and by recreationally active participants.

On the other hand, the present study concluded that during single leg hopping, the sequence of percentage moment contribution was knee extensor moment (43.13%) then ankle plantar flexor moment (37.26%) and hip extensor moment (19.61%) for the involved (injured) limb. The same sequence (with different magnitudes of contribution) was reported in the non involved limb (non injured). The difference in the percentage of contribution from jogging to hopping may be attributed to the landing strategies in hopping that require higher shock absorbing capacity from the knee joint than jogging. This explanation is in agreement with Ortiz et al (2008) who studied the landing strategies in terms of hip and knee kinematics, kinetics, and electromyography during single-legged drop jump from 40 cm height. The study was performed on 13 women with old ACL reconstruction from (1-16) years. Data were compared with those of a control group of a 15 healthy women. The EMG data were collected from quadriceps, lateral and medial hamstrings, and gluteus maximus muscles. The authors found significant increase in the co-contraction of quadriceps and hamstring, and gluteus maximus muscles of the operated limb compared with the non-operated limb and control group. While there were no significant differences found between groups regarding the hip and knee angles and extension moments. Authors suggested that women with ACL reconstruction had landing strategies similar to the non-injured women with regard to the joints' kinematics. The study is limited by wide range of post-operative time spent before assessment, more than one type of autografts were used for reconstruction, and the unmatched control group (Ortiz et al., 2008).

The previous findings were in contrast with the studies of Nyland et al. (1997) and Coventry et al. (2006). Nyland et al. (1997) assessed the effects of quadriceps and hamstring muscles fatigue on the lower limb moments on 20 female college students during crossover cutting. The data were collected before and after the muscle fatigue. First the subjects were trained to become familiar with the eccentric isokinetic quadriceps and hamstring exercises. The peak torque of these muscles were determined. The exercises were continued with maximum effort to induce fatigue which were reached when a 20% reduction in the peak torque was observed. It was found that hamstring fatigue resulted in decreased peak knee and ankle flexion moments and increased internal tibial rotation at peak knee flexion. While quadriceps fatigue decreased the peak knee extension moments and delayed the peak knee flexion and increased the peak ankle dorsiflexion moments.

On the contrary, the study of Salem et al (2003) reported that patients performing the squat exercise, within 1 year of ACL reconstructive surgery, used 2 strategies for generating the joint torques required to perform the movement: (1) in the noninvolved limb, patients used a strategy that equally distributed the muscular effort between the hip and knee extensors, and (2) in the involved limb, patients used a strategy that increased the muscular effort at the hip and reduced the effort at the knee. The contradiction between their study and the current study may be due to the nature of exercise performed (squatting in their study and jogging and hopping in this study). In addition in the current study the measurements were taken after application of fatigue protocol.

Furthermore, in the study conducted by Coventry et al. (2006), ten active males practiced a specific fatigue landing protocol which involved a sequence of single-leg landing on the dominant leg from an overhead trapeze bar, maximal single-leg countermovement jumps, and five single-leg squats. This sequence was repeated until exhaustion. The kinematic, and kinetic data were collected before and after fatigue by using a motion monitor electromagnetic tracking system and a force platform. The authors didn't find a significant difference in the values of lower limb extensor moments of the dominant leg both before and after the fatigue protocol but reported that with fatigue there was an increase in the hip and knee flexion angles while the ankle plantar flexion was decreased. Thus the hip joint work increased and this may be a compensatory mechanism to maximize the activity of gluteus maximus muscle as a hip extensor to absorb the mechanical energy at the impact.

The insignificant differences found between the injured and non injured limb is also supported by Flanagan et al (2008) who concluded that after ACL reconstruction, rehabilitated participants did not exhibit deficits in force production or reactive strength capabilities. Their results suggested that force production and reactive strength capabilities can be restored to levels comparable with the uninjured control limb and may not be limiting factors in ACL recovery. This was in contrast with the study of Ageberg et al (2009) who concluded in their study that the lower hamstring muscle power, and the lower hamstring to quadriceps ratio in the hamstring tendon graft group than in the patellar tendon graft group 3 years after ACL reconstruction, reflect imbalance of knee muscles after reconstruction with hamstring graft that may have a negative effect on dynamic knee-joint stabilization. It was also in contrast with the study of Mattacola et al (2002) who concluded that on the single-leg hop for distance, the ACL reconstructed subjects hopped significantly shorter distances with the involved limb than the uninvolved limb. Furthermore, the ACL reconstructed subjects' single-leg hop distance was significantly less when the involved limb was compared with the control-group matched involved limb, and the ACL reconstructed subjects performed significantly better when the uninvolved limb was compared with the control-group matched uninvolved limb. The ACL reconstructed subjects produced significantly greater torque in the uninvolved leg than in the involved leg. In addition, the peak torque was significantly less for the involved limb in the ACL reconstructed group when compared with the matched involved limb of the control group. The difference between the current study and the previous studies may be attributed to the nature of measurement procedures, gender of patients, type of ACL reconstruction and duration after surgery.

The difference in landing strategies of the lower extremity and energy absorption landing style between males and females were examined by Decker et al., (2003) in order to investigate the gender differences in these parameters. Twenty one recreational athletes (twelve males and nine females) were recruited for this study and were instructed to land from a 60 cm box with arms folded across the chest, upon a force plate while capturing by a five cameras motion analysis system, the authors reported that females landed with a more erect posture to maximize the energy absorption from the ankle joint. The authors also evaluated the peak joints power and work as indicators for the energy absorption, the results suggested that both genders had high knee extensors power and both utilized the knee as the primary joint for shock absorption. The second largest contributors to energy absorption were the hip extensors and ankle plantar flexors. There were several limitations in this study that were not mentioned, first the sample wasn't randomly selected, and the female and male groups were not of equal size, in addition to, it was better to hide the force plate to avoid targeting by the subjects. These limitations led to a very limited external validity of this study.

6. CONCLUSION:

The rehabilitation program of ACL should take into consideration the type of sport that the subject will return to. If the sport is concentrated on hopping, the rehabilitation program might emphasize on knee extensor mechanism followed by hip extensor moments and then ankle plantar flexors. On the other hand, if the sport requires more jogging, the sequence of training program is better to focus on plantar flexors, then knee extensors and lastly hip extensors.

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