MUSCLE ACTIVITY DURING GAIT ON A TREADMILL: A COMPARISON BETWEEN ANTERIOR CRUCIATE LIGAMENTS (ACL) AND NORMAL SUBJECT'S

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The aims of this research are to investigate and compare the muscles activity during gait on a treadmill for ACL subjects who underwent surgery and did not undergo surgery, and comparing them with normal subjects. The question that need to be solved is do the ACL subject who underwent or did not undergo surgery shows similar muscles force compared to normal subject? Walking activity of 12 subjects on a treadmill were captured using Vicon Nexus system and electromyography (EMG) and analyzed. As a result, the comparison between ACL subjects shows that subject who underwent and did not undergo surgery used mainly soleus and gluteus maximus muscles, similar to normal subjects but the muscle forces produced were different. Besides, range of all ACL subjects' muscles who went through surgery was found to be similar to normal subject's.

KEY WORDS: Anterior Cruciate Ligament (ACL), Electromyography (EMG)

INTRODUCTION: Ligaments are structures that hold femur and tibia and help controlling the movements of the joints. Most of ligament injuries occurred to anterior cruciate ligament (ACL) caused by sport activities (Negahban et al., 2013; Almeida et al., 2014; Junior et al., 2015; Meer et al., 2014), recreation and ski (Guenoun et al., 2012), military activities and road traffic accident (Tengku et al., 2013). Long term injury of the ACL may cause the knee to lose its function and to be unstable. This will consequently injures the meniscus (Herbert et al., 2015) which purposes are to smoothen knee movement and act as shock absorbance. One of the most well-known reconstruction methods of ACL is by using tendon to replace the injured ACL, introduced by Jones in 1963 (Stringham et al., 1996). However, the effects of this surgery on muscles activities remain unknown. Therefore, the purpose of this study is to investigate and compare the muscles activity of ACL subjects who underwent and did not undergo ACL surgery during gait on a treadmill, and comparing them with normal subject.

METHODS: The experiment involved gait activity of six ACL and six normal subjects on a treadmill. Movements of the lower limb were recorded using EMG systems and Vicon motion capture. EMG was used to record the changes of the electrical impulse during muscle contraction emitted by the motor nerve impulse that was channelled through the muscles (Gazlia, 2013). The selected muscles were the gluteus maximus (GLM), bicep femoris (BF), semitendinosus (ST), rectus femoris (RF), vastus lateral (VL), tibialis anterior (TA), gastrocnemius (GA) and soleus (SO). Data was collected on both legs of the ACL and control subjects. At the beginning of the EMG experiment, maximum voluntary contractions of the muscles (MVC) of the subject were recorded. The highest values of MVC were recorded during contraction. The maximum muscle activation was obtained during flexion and extension of the ipsilateral leg. After 10 minutes break, gait experiment was carried out. The ACL subject was required to perform a repetitive of 20 seconds of gait activity on a treadmill. The data were processed using the EMG Works analysis version 4.0.7 and stated as raw EMG data. The final step was to calculate the muscle stress using Maple software. Raw EMG data was fitted using Butterworth 'band pass' filter. Since the subset data was in repeated cycles, data selected would go through a 'low pass' filter. Then after a calculation for the subset data, normalization was performed.

Ten trials were taken for each calculation. At this stage, the average values of all subjects of EMG data for each muscle during activity ($\boldsymbol{X}$) were taken and divided with MVC data ($\boldsymbol{Y}$),

$$Z = \sum_{i=0}^{n} \frac{X}{Y} ; \text{ n= 1,2,...,}$$

where Z = EMG/MVC value (%), X_i = Muscle's EMG value during an activity, Y_i = MVC of i_{th} muscles. The obtained values (Z) were multiplied with a maximum force, *fmax* to obtain the force (F_i) for each muscle,

$$F_i = Z \times fmax$$

where *fmax* value was obtained by multiplying the maximum stress and the physiological cross-sectional area (PCSA). Maximum stress was fixed at 250 kPa (Bronzino, 2000) and PCSA for each muscle was based on Arnold and others (2010) as shown in Table 1.

TABLE 1: Physiological Cross-Sectional Area (PCSA) value

Muscle	PCSA (cm²)
Contralateral and ipsilateral Tibialis anterior, f_1	11.0
Contralateral and ipsilateral Soleus, f_2	58.0
Contralateral and ipsilateral Gastrocnemius, f_3	21.0
Contralateral and ipsilateral Vastus lateral, f_4	37.0
Contralateral and ipsilateral Rectus femoris, f_5	14.0
Contralateral and ipsilateral Bicep femoris, f_6	12.0
Contralateral and ipsilateral Semitendinosus, f_7	4.0
Contralateral and ipsilateral Gluteus maximus, f_8	36.0

Source: Arnold et al., (2010)

At the same time, Vicon Nexus system was used to obtain five frame times during gait which were heel off, toe off, initial and mid-swing, foot flat and back to heel off. Motions of subjects were captured using three Vicon Nexus infrared cameras (two MX3+ and one MXF20) with speed of 100Hz. 16 reflective markers were placed on the anatomical landmarks of subject's lower limb which were the right and left anterior superior iliac (RASI, LASI), the right and left posterior superior iliac (RPSI, LPSI), right and left thigh (RTHI, LTHI), right and left knee (RKNE, LKNE), right and left tibia (RTIB, LTIB), right and left ankle (RANK, LANK), right and left toe (RTOE, LTOE), and right and left heel (RHEE, LHEE). The data were digitized by using Vicon Nexus 1.5.2 motion analysis system. Each frame time was synchronized with EMG to obtain the muscle force (Rajtukova et al., 2014).

RESULTS AND DISCUSSION: Table 2 shows the results of average value of ACL subjects' muscles that did and did not undergo surgery and normal subjects in five frame times during gait experiment. Three of six ACL subjects went through operation on the ipsilateral leg and the other three ACL subjects did not undergo operation on the injured contralateral leg. Therefore, the research focused and took measurement on the ipsilateral leg for the injured contralateral leg put on loads on ipsilateral leg. This is because the ipsilateral leg takes over parts of load from the contralateral leg during walking. Five frame times with particular active muscles during gait activity on the treadmill are GA and SO during heel off, RF during toe off, RF, BF and ST during initial and mid-swing, RF and VL during foot flat (double support phase) and GA and SO during back to heel off (Rajtukova et al., 2014). In this experiment, all subjects went through the same phases and the muscle forces produced were different. For normal subject, the most active muscle were GLM and SO during heel off, RF and SO during toe off, GLM and SO during initial and mid-swing, foot flat and back to heel off. Some of these active muscles are the same as stated by Rajtukova's study. The other active muscles that were stated by Rajtukova were also active in this study, but showed a lower muscle force. The comparisons were done between ACL subjects. Based on the results of Table 2,

subject who went through surgery used mainly SO and GLM muscles in every frame times but the muscle forces produced were different. ACL subject that did not undergo surgery however used mainly VL and SO during heel off, GLM and VL during toe off, GLM and SO during initial and mid-swing and back to heel off and GLM during foot flat, but GLM and SO were still among the most active muscles, similar to ACL subjects that underwent surgery. The range value of SO muscles for ACL subjects who went through surgery was higher of 14000 N to 33000 N compared to ACL subjects that did not undergo surgery of 6700 N to 19000 N. GLM muscle was the second most active muscle during gait. Muscle force value of ACL subjects' GLM muscles that went through surgery were higher compared to ACL subjects that did not undergo surgery and ranged between 8100 N to 11000 N. ACL subject who did not undergo surgery shows higher muscle force on BF, ST, RF, VL, TA and GA for all frame times. This proved that the effect of not undergoing surgery on the contralateral leg will put on load to the ipsilateral leg during walking. Normal subjects also used mainly SO and GLM muscle during walking as shown in Table 2. Average value of ACL subjects' muscles that went through surgery was found to be similar to normal subjects in five frame times compared to that of subject who did not undergo surgery. This shows that undergoing surgery produced ligaments with more stable and stronger muscle force compared to those that did not undergo surgery. Besides, the range of ACL subjects' muscle that did not undergo surgery was lower and not similar compared to normal subjects because of the unbalanced distribution of muscle forces as shown in Table 2.

TABLE 2: Average value of ACL subjects' muscles who (a) went through, (b) did not undergo surgery and (c) normal subjects' in five frame times during gait experiment

Gait Phase	Muscle Force (N)							
	GLM	BF	ST	RF	VL	TA	GA	SO
Heel off	8156	728	174	5438	5764	244	841	15745
Toe off	9815	437	156	5035	9117	185	818	14341
Initial and mid-swing	10503	608	187	5974	7304	244	1151	22701
Foot flat	10941	535	232	4056	8329	271	1511	31336
Heel off	10545	721	221	8405	9449	420	1611	32949

(a)

Gait Phase	Muscle Force (N)							
	GLM	BF	ST	RF	VL	TA	GA	SO
Heel off	8071	1574	578	669	8778	4136	6218	13092
Toe off	8900	1315	277	5965	8914	5250	4359	8112
Initial and mid-swing	10154	1599	400	6716	7638	3736	6186	18941
Foot flat	10435	1617	299	6317	6454	4525	3364	6715
Heel off	10276	1719	310	6235	7937	6664	7236	18781

(b)

Gait Phase	Muscle Force (N)							
	GLM	BF	ST	RF	VL	TA	GA	SO
Heel off	17841	3396	4743	8634	8445	997	3392	14928
Toe off	9967	2493	1029	10110	8392	957	4030	10370
Initial and mid-swing	11913	2590	1451	6647	8842	1112	3156	13527
Foot flat	12554	2559	1329	9143	8948	846	3623	12821
Heel off	11613	2966	1685	8943	9816	941	3559	15886

(c)

CONCLUSION: This study concluded that normal subjects used mainly SO and GLM muscles during gait on a treadmill. ACL subjects who underwent through and did not undergo surgery showed similar active muscles which were SO and GLM like normal subject but different muscle force was produced. ACL subjects who underwent through surgery showed similar values of SO and GLM muscles force like normal subject. However, BF, ST, RF, VL, TA and GA muscles force were not similar to normal subject. ACL subjects tend to put greater force and load of more than 10000 N on SO muscles during gait. Besides, GLM muscle was the second muscle used during gait as shown in Table 2.

REFERENCES:

Almeida, A., Valin, M. R., Ferreira, R., Almeida, N. C. D. & Agostini, A. P. (2014). Correlation between the result from arthroscopic reconstruction of the anterior cruciate ligament of the knee and the return to sports activity. *Revista Brasileira de Ortopedia,* **49**(3), 240-244.

Arnold, E. M., Ward, S. R., Lieber, R. L., & Delp, S. L. (2010). A model of the lower limb for analysis of human movement. *Annals of Biomedical Engineering,* **38**(2), 269-279. Bronzino, J. D. (2000). *The Biomedical Engineering Handbook, Volume 1*. USA & Germany: CRC Press & Springer-Verlag.

Gazlia. (2013). Optimization of spinal muscular atrophy subject's muscle activity during gait. Dissertation Master of Science, Faculty of Science and Techonolgy, National University of Malaysia.

Guenoun, D., Le Corrollera, T. L., Amousa, Z., Paulya,V., Sbihib, A. & Champsaur, P. (2012). The contribution of MRI to the diagnosis of traumatic tears of the anterior cruciate ligament. *Diagnostic and Interventional Imaging,* **93**(5), 331-341.

Herbert, A., Jones, G. L., Ingham, E. & Fisher, J. (2015). A biomechanical characterisation of A cellular porcine super flexor tendons for use in anterior cruciate ligament replacement: Investigation into the effects of fat reduction and bio burden reduction bioprocesses. *Journal of Biomechanics,* **48**(1), 22-29.

Junior, O. D. M. S. J., Ohashi, B. D. N., Almeida, M. O. D. & Goncalves, M. R. (2015). Functional result relating to the positioning of thegraft in anterior cruciate ligament reconstruction. *Revista Brasileira de Ortopedia,* **50**(1), 57-67.

Meer, B.L. V., Waarsing, J. H., Eijsden, W. A. V., Meuffels, D. E., Arkel, E. R. A. V., Verhaar, J. A. N., Bierma-Zeinstra, S. M. A. & Reijman, M. (2014). Bone mineral density Changes in the knee following anterior cruciate ligament rupture. *Osteoarthritis Society International,* **22**(1), 154-161.

Negahban, H., Ahmadi, P., Salehi, R., Mehravar, M. & Goharpey, S. (2013). Attentional demands of postural control during single leg stance in patients with anterior cruciate ligament reconstruction. *Neuroscience Letters,* 550, 118-123.

Rajtukova, V., Michalikova, M., Bednarcikova, L., Balogova, A. & Zivcak, J. (2014). Biomechanics of Lower Limb Prostheses. *Procedia Engineering,* 96, 382-391.

Stringham, D. R., Pelmas, C. J., Burks, R. T., Newman, A. P. & Marcus, R. L. (1996). Comparison of anterior cruciate ligament reconstructions using patellar tendon autograft or allograft. *Arthroscopy: The Journal of Arthroscopic and Related Surgery,* **12**(4), 414-421.

Tengku, T. T. M. S., Ahmad, S., Kasmin, M., Nor, M. M., Daud, M. F. & Hamdan, M. A. (2013). The activity leading to ACL injury and the ability to resume duty following reconstructive surgery in Malaysian military patients. *The Medical Journal of Malaysia,* **68**(2), 115-118.

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