Preventing Anterior Translation of the Human Knee Joint by Contracting the Biceps Femoris Muscle Using an Accelerometer and an Electrical Muscle Stimulator Device

Haluk Hayri Öztekin,
Beykent University, School of Health Sciences,
Department of Physiotherapy and Rehabilitation,
Beylikdüzü, İstanbul, Turkey
halukh1@yahoo.com

Nuri Süha Bayındır*, Aytug Guner
*Department of Electrical and Electronic Engineering
İzmir University of Economics
İzmir, Turkey
nuri.bayindir@ieu.edu.tr, aytuggun@gmail.com

***Abstract*—This paper presents the design, implementation and the test results of a "Prophylactic Anti-Translational Electronic Knee Brace" which detects the abnormal anterior translation of the tibial bone in the knee joint caused by an anterior cruciate ligament rupture. With the help of a three axes wireless acceleration sensor, the agonist biceps femoris muscle is contracted in real time, using a microcontroller based electrical muscle stimulator (EMS), at the instant when the acceleration of the tibia exceeds a limit value. The waveforms of the modulus of the three axes acceleration components and the EMS pulses applied to the right and left knees of a healthy subject, during the extension and flexion tests on the knee joint are presented simultaneously and discussed. It was observed that, the EMS pulses are generated with a delay of 40 msec and contracted the biceps femoris muscle successfully, at the instant when the acceleration limit is exceeded.**

Keywords —anterior cruciate ligament; anterior translation; knee brace; acceleration sensor

I. INTRODUCTION

The anterior cruciate ligament (ACL) provides resistance to tibial internal rotational torque and anterior shear force at the knee [1] [2] [3] [4] [5]. However, when ruptured, ACL deficiency results with knee instability [5] [6]. This instability can be clinically diagnosed and easily quantified by three tests. Those are a manual Lachman test, a Lachman test with devices like the KT-1000 device (MEDmetric Corp, San Diego CA, USA) and a pivot shift test with devices like the KiRA device [5] [6].

The most specific and sensitive clinical test for detecting pathological anterior tibial translation is the Lachman test [5] [7]. On the other hand, in a recent study of Raggi [6] et al, the KiRA device have also shown excellent inter- and intra-tester repeatability detecting ACL deficiency. When compared with the Lachman test, no significant difference was found between these two tests.

Optimization of muscle contraction through functional electrical stimulation (FES) offers the prospect of mitigating the destabilizing effects of ACL deficiency [1]. The hypothesis of Azmi et al. [1] is that, external activation of the biceps femoris long head (BFLH) reduces the tibial internal rotational torque and the anterior shear force at the knee. This study revealed that while the FES significantly reduces the tibial internal rotational torque at the knee, it could also reduce the anterior shear force to zero. However, this method was applied only on healthy subjects and has not yet been tested on ACL deficient subjects to consider its effect in mitigating instability due to ligament deficiency. Application of this test on an ACL deficient subject requires the accurate detection of the anterior translation of the knee.

Solomonow [2] has designed a system for maintaining the knee stability of a patient suffering from damage of knee ligaments. In this work, a potentiometric angle sensor, an anterior/posterior displacement sensor and a force sensor were used to detect the pivot shifting in the knee joint and provide feedback information to trigger an electronic stimulator whenever an abnormal shift of the tibia occurs. The main drawback of this method is that, any delays in detecting the start of the anterior translation may cause harmful effects on the muscles, ligaments and nerves of the patient. However, with the advent of the state of the art three axes micro electromechanical acceleration sensors, the anterior translation of the tibia can be detected much faster and accurately than the angle, displacement or force sensors [3].

Acceleration sensors are specialized instruments which typically contain an accelerometer to measure linear acceleration using an inertial mass which is attached to a frame with a spring [8]. When the sensor is accelerated by an external force, it begins to move along the direction of force while the inertial mass remains in its resting state due to inertia. There is a device in the market (KiRA-Orthokey-Italy) that determines the instant of the knee's giving way- anterior translation-snapping by the help of a physician [3]. In this work, a wireless three axes acceleration sensor and a software were used to monitor the acceleration waveform on a tablet [3]. Although this device detects and monitors the instant of anterior translation and pivot shifting accurately, it does not incorporate a feedback control

978-1-7281-2420-9/19/$31.00 ©2019 IEEE

system in order to use this information to prevent the initiation of anterior translation of the knee in an ACL deficient patient.

Although there are many mechanical knee braces [9] which claim to prevent the instability of the knee in ACL injured patients, there is no scientific evidence regarding their benefits. From the knee injury prevention point of view in ACL torn knees, the antagonist muscles of ACL are Quadriceps and Gastrocnemius; agonist muscles are essentially the Hamstring and Soleus muscles [10]. Reflex contraction in the Hamstring muscles when ACL is strained, which is proved by the in vivo and in vitro studies, is called the "Hamstring-ACL" reflex arc. Our present work was inspired from this physiological reflex arc [10] [11].

II. DESCRIPTION OF THE PRESENT WORK

The present method is directed to an anti-translational electronic knee brace which will prevent the pathological anterior translation of the knee of a patient, by determining the start of the translation of the knee, using a 3 axes acceleration sensor and contracting the biceps femoris muscle through the use of a pulse generator via the electrodes attached to the posterior thigh of the patient as shown in Fig. 1.

The 3 axes acceleration sensor MPU6050 [12] coupled with an arduino nano microcontroller as shown in Fig. 2 is attached on the lower leg of a volunteered patient, with an antiallergent adhesive band after receiving a written consent from him. The critical position at the abnormal motion of the knee is determined by using the modulus of the 3 axes acceleration values from the sensor.

At the instant when the critical shift position is detected, the microcontroller on the acceleration sensor circuit produces a warning signal and sends it to the wireless EMS device via a Bluetooth device. The warning signal received by the wireless receiver is transferred to the microcontroller as shown in Fig. 3. At this instant, the EMS microcontroller produces asymmetric-biphasic pulse signals at the appropriate frequency, pulse width and period, calibrated according to the patient's muscular responses to contract the hamstring muscles.

Based on the results of the tests applied on the healthy leg hamstring muscle of the patient, the tibia position at the trigger instant of the hamstring muscle is determined and the threshold of the warning signal is adjusted in the program of the microcontroller with respect to the patient. Finally, the PWM pulse signal parameters required to contract the hamstring muscles are also determined according to the patient's biophysical features and is updated in the microcontroller control program.

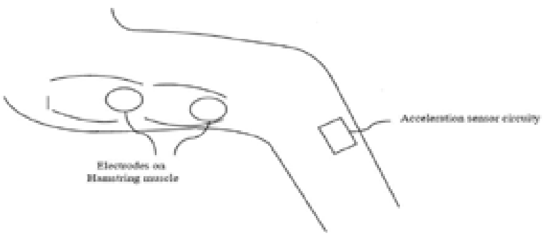

Fig. 1. Position of the device on the right lower extremity

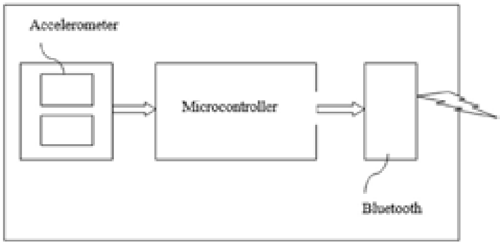

Fig. 2. Acceleration sensor circuit

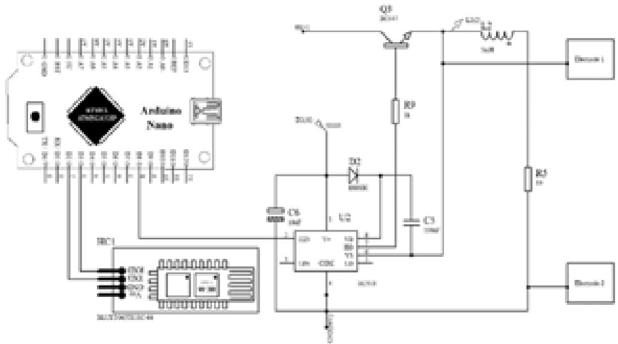

Fig. 3. Asymmetrical biphasic pulse generator circuit diagram

III. DESIGN OF THE EMS CIRCUITRY

As the EMS circuitry is supplied with a 5 V battery, the PWM signals at 5 V generated by the 555 timer are increased to the voltage levels of 50 – 100 V, required to contract the Hamstring muscle, using the boost converter of [13].

Most EMS units utilize an asymmetrical biphasic waveform which eliminates the problem of producing a net skin charge which could lead to possible burns on the skin [14]. Asymmetrical biphasic waveforms have two phases, an active phase and a balancing passive phase. In the active phase the positive going current travels through the positive electrode into the tissue, and during the balancing phase the current returns out the negative electrode hence no net charge is left at the skin to cause burns.

An asymmetrical biphasic circuit diagram of Fig. 3 is designed by using a chopper circuit where the pulses are generated by switching the NPN transistor ON and OFF at a frequency of 50 – 100 Hz with a duty ratio of 1 – 10%. The pulses are initiated by an arduino nano which receives the firing signal at the starting instant of the anterior translation from the accelerometer via a bluetooth. An inductor of 5 mH is used to store energy when the transistor is ON, while applying positive voltage to the electrodes, and apply negative voltage at the electrodes when the transistor turns OFF.

IV. TEST RESULTS

Mainly two tests are conducted using the systems developed in this work.

A. Lachman and Anterior Drawer Tests

Lachman and anterior drawer tests are applied at almost knee extension and flexion with the same maximum manual loading and repeated three or four times, on the ACL deficient and healthy legs of a volunteered patient by the senior author who is experienced in ACL surgery. The critical position at the abnormal motion of the knee is determined by using the modulus of the 3 axes acceleration values from the sensor. During the application of three or four manual anterior forces, the acceleration modulus data was recorded on a digital oscilloscope. These pulse waveforms indicate the starting point of the anterior translation in the patient's knee.

Fig. 4 and Fig. 5 summarize the waveforms of the modulus of the 3 axes acceleration components, recorded by the acceleration sensor, during the extension and flexion tests (Lachman and anterior drawer) on the right and left knee of a volunteered patient. Both Lachman tests (in extension) resulted in a significant difference as shown in Fig. 4.

B. Feedback Control Tests on the Complete System

A complete test including the acceleration sensor and the EMS system was applied on a volunteered healthy subject as a proof of our concept where the EMS pulses were generated with a delay of 40 msec, following the instant when the acceleration limit is exceeded. This delay was observed to be reasonably short where the pulses generated by the EMS had enabled successful contraction of the hamstring muscle.

Three pulses were applied to the hamstring muscle of a healthy subject at a frequency of 100 Hz as shown in Fig. 6. Fig. 7 shows the details of each pulse where the peak values of the positive and negative pulses are 56 V and -34V respectively. The pulse widths of the positive and negative pulses are 140 µs and 100 µs respectively. It was observed that when the three pulses, whose measured values depicted as above, were applied by the EMS module at the instant determined by the accelerator, the hamstring muscle contracted as expected.

As a future work, the shift in the tibia will be calculated by integrating the acceleration values to find the velocity and then further integrating the velocity to get the displacement. The displacement of the tibia, in conjunction with the modulus of the acceleration, will be used to determine the trigger instant of the EMS circuit.

We are expecting to receive the approval of the ethical committee in order to implement those tests to the patients with anterior cruciate ligament (ACL) deficiencies for a future study. Electrodes of the stimulator device are attached to the appropriate positions of the hamstring Muscle (Biceps femoris) using an antiallergic adhesive bandage and the wireless stimulator device is housed inside a pocket sewed on the bandage. The wireless sensor and the stimulator devices are operated with Li-Ion batteries and there is an adaptor input connector on the device to enable the charging of the EMS.

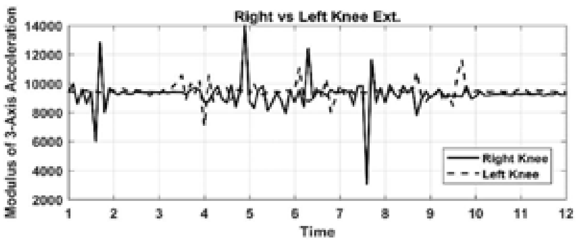

Fig. 4. Comparison of lachman tests on both Knees

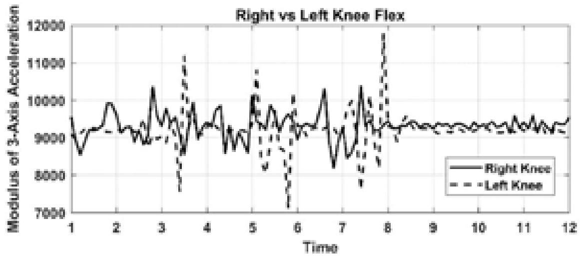

Fig. 5. Comparison of anterior drawer tests on both knees

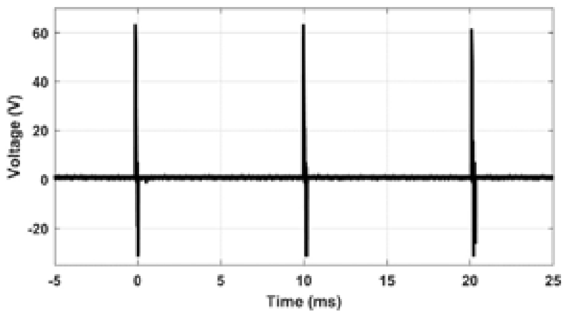

Fig. 6. Pulses generated by the EMS circuit and applied to the muscles

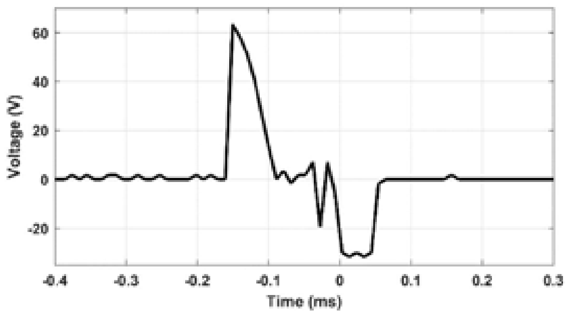

Fig. 7. Details of a single pulse generated by the EMS circuit

V. MEDICAL DISCUSSION

There is a subset of ACL deficient patients who are able to return to pre-injury activity without surgical intervention; these are termed copers [1]. Coping is achieved through avoiding muscular contraction that produces an anterior shear force, for example, avoiding full contraction of the quadriceps especially during the early stance phase and when the knee is at full extension [15]. An alternative coping mechanism counteracts quadriceps contraction through co-contraction of the hamstrings [16], and through the adaptation of muscle firing. The other set is that of non-copers who undergo ACL reconstruction surgery, where there may be a residual internal rotation instability. Prior work has shown that activating muscles around the knee with functional electrical stimulation (FES) is able to reduce anterior tibial translation (ATT), a surrogate measure of the anterior shear force [1]. It has also been shown that FES, assisted with a knee brace, can be used to learn a muscle contraction pattern that then, once learned, persists despite halting the use of FES [1]. Thus, the underpinning hypothesis of this work is that FES can restore normal ATT at the lateral compartment of the knee by entraining the contraction of specific knee muscles. We hypothesize that, our methodology will develop the coping skills of the patients during the rehabilitation period when both devices work simultaneously.

Preventive medicine is always the priority in medical practice. The ultimate purpose of the present work is to determine the start of the abnormal motion of the tibia, while the patient is in motion, and prevent the abnormal translation of the knee joint, by contracting the hamstring muscle in real time, using an EMS device whose electrodes are attached to the patient's leg. Our expectation is this system will primarily protect the healthy ACL of the athletes and also help the removal of the complaints of the patients who feel loosening and translation in their knees and will probably constitute an alternative preventive treatment to surgical operations. On the other hand, the rehabilitation period of the patients who had a surgical operation will be shortened because the use of the device will protect the reconstructed ACL.

VI. CONCLUSION

A Prophylactic Anti-Translational Knee Brace is designed and constructed to detect the abnormal translation of the knee joint, caused by ACL deficiency, by using a 3 axes wireless position and acceleration sensor circuitry and contract the agonist biceps femoris muscle in real time using an EMS device. The waveforms of the modulus of the 3 axes acceleration component during the Lachman and anterior drawer tests on the right and left knee of a patient are presented and discussed. Although the EMS system has been constructed and tested completely, EMS pulses are not yet applied to the patient's muscle as we are expecting to receive the consent of the ethical committee in order to implement these tests on a patient. Meanwhile, the knee brace will be used as a data logger to record the acceleration values of a patient during walking and these data will be used to calibrate the EMS device.

A complete test including the acceleration sensor and the EMS system was applied on a volunteered healthy subject as a proof of our concept. The waveforms of the modulus of the 3 axes acceleration components and the EMS pulses applied to the right and left knees of a healthy subject, during the extension and flexion tests are presented simultaneously. It was shown that, the EMS pulses are generated with a delay of 40 msec, following the instant when the acceleration limit is exceeded. In the future clinical practice, activating the hamstring muscle, especially biceps femoris, may be used to protect ACL reconstructions during post-operative rehabilitation, will assist with residual instabilities post reconstruction, and reduce the indications for ACL reconstruction surgery in some cases. A "learned" conditional reflex is expected to occur in the extrapyramidal or limbic system and this reflex may eliminate the need for using the electronic knee brace continuously in the future.

REFERENCES

[1] N. L. Azmi, Z. Ding, R. Xu, and A. M. J. Bull, "Activation of biceps femoris long head reduces tibiofemoral anterior shear force and tibial internal rotation torque in healthy subjects," *Plos One*, vol. 13, no. 1, 2018.

[2] M. Solomonow, "Sensory – Motor control of ligaments and associated neuromuscular disorders," *Journal of Electromyography and Kinesiology*, vol. 16, no. 6, pp. 549–567, 2006.

[3] N. Lopomo, S. Zaffagnini, C. Signorelli, S. Bignozzi, G. Giordano, G. M. M. Muccioli, and A. Visani, "An original clinical methodology for non-invasive assessment of pivot-shift test," *Computer Methods in Biomechanics and Biomedical Engineering*, vol. 15, no. 12, pp. 1323–1328, 2012.

[4] S. Zaffagnini, C. Signorelli, A. Grassi, H. Yue, F. Raggi, F. Urrizola, T. Bonanzinga, and M. Marcacci, "Assessment of the pivot shift using inertial sensors," *Current Reviews in Musculoskeletal Medicine*, vol. 9, no. 2, pp. 160–163, 2016.

[5] A. Benjaminse, A. Gokeler, and C. P. V. D. Schans, "Clinical Diagnosis of an Anterior Cruciate Ligament Rupture: A Meta-analysis," *Journal of Orthopaedic & Sports Physical Therapy*, vol. 36, no. 5, pp. 267–288, 2006.

[6] F. Raggi, T. R. D. Sarsina, C. Signorelli, G. M. M. Muccioli, L. Macchiarola, I. Cucurnia, M. Romagnoli, A. Grassi, and S. Zaffagnini, "Triaxial accelerometer can quantify the Lachman test similarly to standard arthrometers," *Knee Surgery, Sports Traumatology, Arthroscopy,* 2018.

[7] C. C. Prodromos and B. J. Murphy, "Diagnosis and Nonoperative Treatment of Anterior Cruciate Ligament Tears: Diagnosis of Anterior Cruciate Ligament Tear," in *The Anterior Cruciate Ligament*, Philadelphia, PA: Elsevier, 2018.

[8] "MEMS Accelerometer-Acceleration Transducer, Sensor, Working, Technology," *instrumentation.com*, Aug. 2011. [Online]. Available: http://www.instrumentationtoday.com/mems-accelerometer/2011/08/. [Accessed June 15, 2019].

[9] S. Najibi and J. P. Albright, "The Use of Knee Braces, Part 1: Prophylactic Knee Braces in Contact Sports," *The American Journal of Sports Medicine*, vol. 33, no. 4, pp. 602–611, 2005.

[10] J. J. Elias, A. F. Faust, Y.-H. Chu, E. Y. Chao, and A. J. Cosgarea, "The Soleus Muscle Acts as an Agonist for the Anterior Cruciate Ligament: An in Vitro Experimental Study," *The American Journal of Sports Medicine*, vol. 31, no. 2, pp. 241–246, 2003.

[11] E. Tsuda, Y. Okamura, H. Otsuka, T. Komatsu, and S. Tokuya, "Direct Evidence of the Anterior Cruciate Ligament-Hamstring Reflex Arc in Humans," *The American Journal of Sports Medicine*, vol. 29, no. 1, pp. 83–87, 2001.

[12] "Register Map and Description", *invensense.com*, Aug. 19, 2013. [Online]. Available: https://www.invensense.com/wp-content/uploads/2015/02/MPU-6000-Register-Map1.pdf. [Accessed June 15, 2019].

[13] M. Rezal, N. Mariun, and I. Aris, "Simple boost converter using Timer IC 555 for charging capacitor banks," *2010 IEEE Student Conference on Research and Development (SCOReD)*, 2010.

[14] "Foundations of Electrical Stimulation", *media.lanecc.edu,* Nov. 7, 2011. [Online]. Available: https://media.lanecc.edu/users/thorpeb/pta101 lab/FoundationsofEstim/FoundationsofEstim_print.html. [Accessed June 15, 2019].

[15] R. F. Escamilla, T. D. Macleod, K. E. Wilk, L. Paulos, and J. R. Andrews, "ACL Strain and Tensile Forces for Weight Bearing and Non—Weight-Bearing Exercises After ACL Reconstruction: A Guide to Exercise Selection," *Journal of Orthopaedic & Sports Physical Therapy*, vol. 42, no. 3, pp. 208–220, 2012.

[16] K. S. Rudolph, M. J. Axe, T. S. Buchanan, J. P. Scholz, and L. Snyder-Mackler, "Dynamic stability in the anterior cruciate ligament deficient knee," *Knee Surgery, Sports Traumatology, Arthroscopy*, vol. 9, no. 2, pp. 62–71, 2001.