CONTROL OF THE BOUNDARY CONDITIONS OF A DYNAMIC KNEE SIMULATOR

J. Tiré[1], J. Victor[2], P. De Baets[3] and M.A. Verstraete[2]

[1] Ghent University, Belgium
[2] Ghent University, Department of Physical Medicine and Orthopaedic Surgery, Belgium
[3] Ghent University, Laboratory Soete, Belgium

Abstract: At Ghent University a dynamic knee simulator to analyse the kinematics of a human knee has been developed. The rig is designed to perform tests on a mechanical hinge or on a human knee (with or without a prosthesis). The rig has one degree of freedom in a hip joint and four degrees of freedom in an ankle joint. There is currently one actuator that simulates the quadriceps forces. Two additional actuators are proposed in this paper to simulate the hamstrings forces. The magnitude and phase of the forces varies significantly during the movement (e.g. cycling or squatting). Literature indicates that the maximum muscle forces do not exceed 2000 N. An inverse dynamic analysis, using the musculoskeletal software AnyBody, is proposed to determine the evolution of these forces during the studied movements.

Keywords: Knee Rig; Hamstrings; Biomechanics; Inverse dynamics

1 INTRODUCTION

The knee joint is a complex and vital part of the human body. In case of severe damage, a knee prosthesis might be necessary to optimally restore the knee function. Some patients encounter soaring pain or unbalance during certain movements following total knee arthroplasty (TKA). To understand these problems, the University of Ghent investigates the influence of a prosthesis on the kinematics of a knee.

For this purpose, Ghent University built a dynamic knee rig in collaboration with Ghent University Hospital (UZ Gent). The boundary conditions of the rig (i.e. degrees of freedom and forces acting on the knee) should closely match in vivo conditions to generate useful, valid results. This paper describes the muscle groups that have to be taken into account and translates these into engineering terms (i.e. actuators and control required). To simulate realistic muscle forces, the control of the simulated muscle forces has to be adjusted to the examined movements. The two main movements discussed in this paper are cycling and squatting.

In the remainder of this paper, the knee anatomy is first clarified in section 2. Subsequently, the current design of the dynamic knee simulator is described in detail in section 3. The proposed extension is described in section 4, along with the implementation and numerical methodology to determine the applied force patterns.

2 ANATOMY OF THE KNEE JOINT

To understand the design of the knee rig and the simulated muscle forces, a brief overview of the anatomy of the knee is given. Figure 1a shows an anterior view of the right knee. The knee joint connects the thigh bone (femur) with the shin (tibia) and calf (fibula) bone. The knee cap (patella) rolls over the femur and is attached to the quadriceps muscles on the proximal side and to the shin bone via the patellar tendon on the distal side. The knee joint is considered as a combination of the femorotibial joint (between femur and tibia) and the patellofemoral joint (between femur and patella) [1]. The femur and the tibia are additionally connected to each other with cruciate and collateral ligaments. For a more in depth description of the anatomy of the knee joint, the reader is referred to Blackburn & Craig [2].

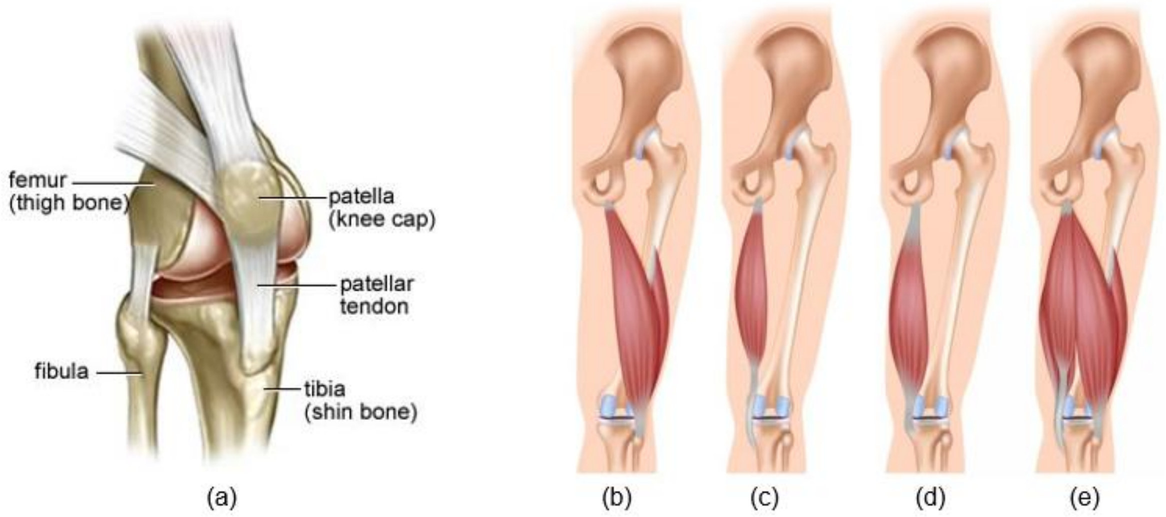

Figure 1 Schematic anterior view of the right knee (a) and posterior view of the dominant hamstring muscles with the biceps femoris caput longum and caput breve (b), semitendinosus (c), semimembranosus (d) and combined view on the hamstring muscles (e) [3]

The most relevant muscles considered in the framework of this paper are the hamstrings. The hamstrings refer to a group of four muscles: the biceps femoris (BF) caput longum (long head), the BF caput breve (short head), the semitendinosus (ST) and the semimembranosus (SM).

Figure 1b to Figure 1e [4] indicate the positions of these muscles. The distal insertion point of both biceps femoris muscles (Figure 1b) is at the fibula. The long head BF has its proximal origin on the pelvis while the origin of the short head BF is located on the femur. Both ST (Figure 1c) and SM (Figure 1d) have their proximal origin on the pelvis and their insertion point on the medial side of the tibia. In Figure 1e a posterior view of the combined hamstrings muscles is shown, where the SM is slightly hidden from sight by the ST. Given the coalescence of their distal insertion point, the BF short head is treated as if it acts as a part of the BF long head in the remainder of this paper.

Apart from the hamstrings, the quadriceps muscles are important. This group consists of four muscles on the frontal side of the femur. The quadriceps are distally connected with the patella and proximally with the femur or the pelvis. The quadriceps group are referred to as extensors of the knee while hamstrings are flexors of the knee. The opposite can be said with respect to the hip joint.

3 GHENT UNIVERSITY KNEE RIG

Research on knee rigs has been conducted for many years and a lot of different designs are reported in literature. The knee rig of Ghent University is based on the Oxford Model, shown in Figure 2a. With this model, the hip joint simulates a combined vertical displacement and rotations in the sagittal (flexion/extension) and coronal (abduction/adduction) plane. The ankle’s translations are restraint, but free in every rotation. This creates six degrees of freedom (DOF) for the knee joint [5].

For the Ghent University (UGent) knee rig, a few adaptations have been made with respect to this Oxford Model. The hip joint does not translate but it is fixed in position with a single degree of freedom, namely rotation in the sagittal plane. The position of the ankle is fixed (and controlled by two actuators) in the sagittal plane but free to translate along the medio-lateral axis. Analogous to the Oxford Knee Rig, the ankle is free to rotate in all three directions. The UGent rig thus has five DOF (one in the hip and four in the ankle).

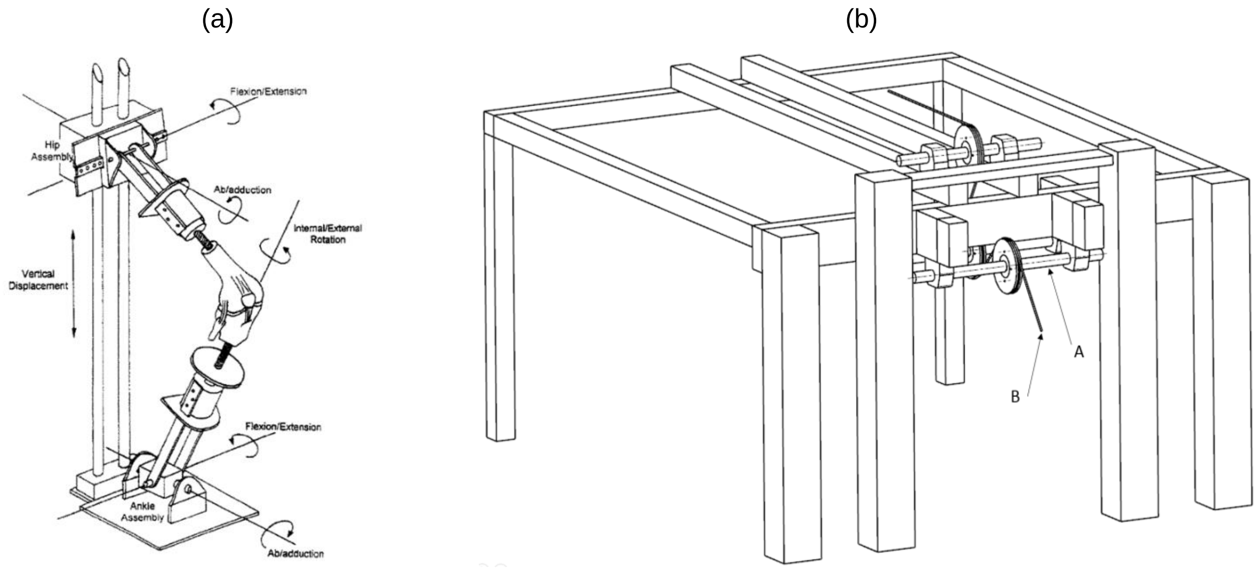

Figure 2 Schematic of Oxford Knee Rig [5] (a) and Ghent University Knee Rig (b)

Tests can be performed with a human knee or with a mechanical hinge, considered as a simplified two dimensional model of a knee joint. When a human knee is used, the femur and the tibia are fixed to the joints in a similar way as for the Oxford model. Figure 2b shows the basic construction of the UGent rig. The centreline of rod A is the centreline of the hip joint. The femur is then connected to this axis. Note that this is a simplified representation of a part of the UGent rig: the actuators, the ankle part and the hinge or knee are not shown.

As mentioned before, the quadriceps and the hamstrings are the two considered muscle groups. At this moment, the rig uses one actuator for modelling the quadriceps force. The quadriceps tendon is therefore connected to the actuator using a pulley system. Figure 2b shows the pulleys needed for the quadriceps force. Pointer B indicates the path of the cable between the attachment on the knee and the piston of the actuator. In this case, the quadriceps actuator is placed horizontally on top of the construction. The force of the actuator is regulated with a control unit using a feedback loop based on the applied force. The amplitude and the profile of this force are educated guesses. The hamstrings forces are not simulated so far, implying additional actuators are needed. The amplitude and evolution of the forces of both quadriceps and hamstrings of course depend on the analysed movement. They need to be calculated for more realistic muscle simulations.

4 HAMSTRINGS ACTUATOR

4.1 Active control of the hamstrings

Since the UGent knee rig uses an actuator for the quadriceps, the muscle force can be controlled and adjusted during any movement. This is not always the case. Some knee rigs just use passive (thus constant) forces to simulate the muscles. In addition, most of the rigs described in literature only simulate the quadriceps force and neglect the hamstrings forces. Although the hamstrings forces are usually smaller than the quadriceps forces, they might still be important with respect to the kinematics of the knee joint.

To illustrate the necessity of an active control for the hamstrings, Figure 3 from Chumanov, Heiderscheit and Thielen [6] is presented. This figure shows the lengthening and the exerted force and power of the three main hamstring muscles during high speed running. During the stance phase of running (flexion of the hip joint and extension of the knee), the hamstrings shorten and exert positive work. During the swing phase the hamstrings lengthen and perform negative work. If a muscle shortens while doing work its contraction is called concentric. If on the other hand the muscle lengthens, it is called eccentric contraction [7].

The forces vary from zero to a maximum of almost 20 N/kg body weight. The maximum force generated by BF, SM and ST occurs during swing face. This is during knee extension and hip flexion, which is expected to be the main activation phase for the quadriceps muscles. The moment of maximum force generation is thus counterintuitive. The explanation for this observation is found in the agonist-antagonist relationship balancing the quadriceps and the hamstrings.

When active muscles cause a certain movement, they are called agonists. Other muscles that cause the opposite movement, are therefore called antagonists. The most common example of agonists and antagonist are the biceps and triceps respectively during flexion of the elbow joint.

When both quadriceps and hamstrings work at the same time, opposite forces and torques are generated. This is not the body's most efficient way to create movement. It is however necessary in certain situations that agonist and antagonist work together (both in other direction) to stabilize joints. In addition, this helps to decelerate the body parts near the end of an applied motion [8]. Note furthermore that BF is an agonist of exorotation of the tibia with respect to the femur and that SM & ST are antagonists of this motion (but agonists of endorotation). That is why they have to work together when flexing the knee without (or with only a small) rotation of the tibia.

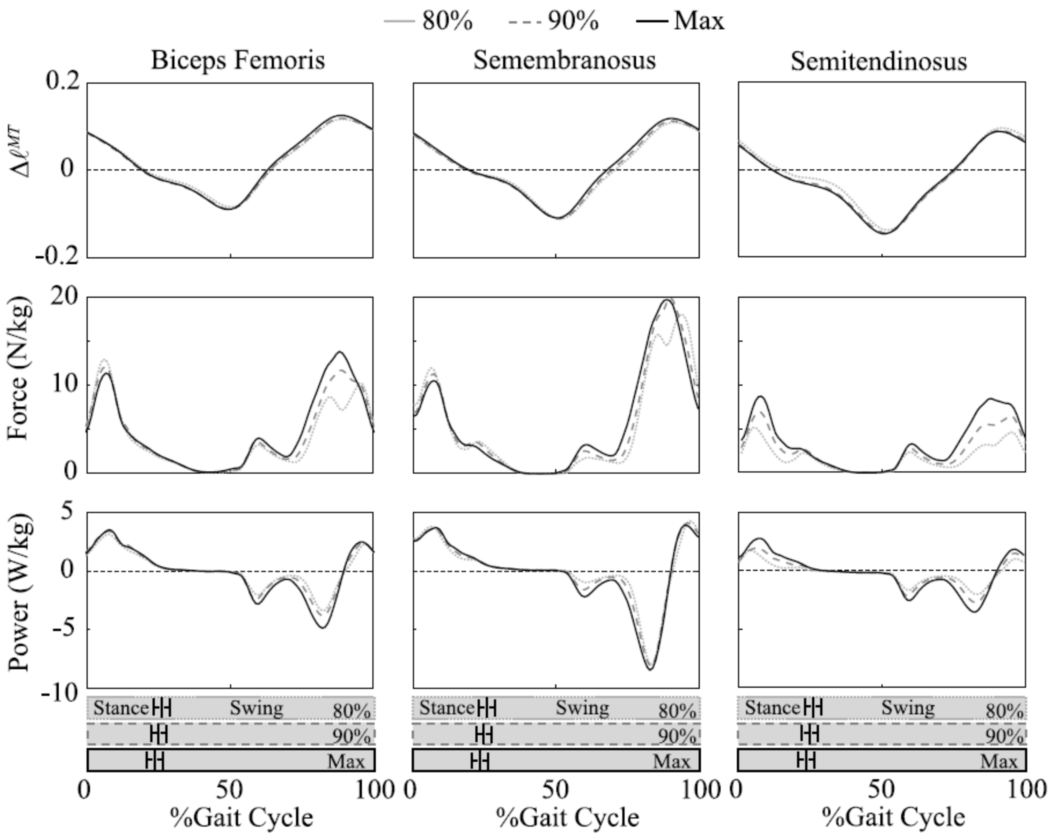

Figure 3 Hamstrings gait cycle analysis [6]

4.2 Implementation into the knee rig

To implement active control of the hamstrings in the knee rig, a few design choices are made. The number of actuators and their stroke and power had to be selected.

The BF distinguishes itself from the SM and ST by its distal insertion point. Because the former attaches on the lateral side and the latter two muscles have their insertion point on the medial side, they have to balance each other to perform stable actions. Since SM and ST are laying on top of each other and their behaviour (see Figure 3) is similar, it was decided to use one actuator for these two muscles and another one for the biceps femoris. Because of the origin of the BF short head on the femur, the muscle cannot be simulated with an external actuator in the current setup. The force of the BF short head is therefore combined with the force of the long head biceps. A vector sum of both simulated muscle forces will define the direction of the actuator.

The same orientations of the muscles are used as in the work of Mesfar and Shirazi-Adl [9]. The BF makes an angle of 11.8° in the frontal plane. The SM and the ST have an opposite (average) orientation of 7°. A pulley system is introduced to assure that the angle of the applied force remains close to the in vivo situation. Because the SM and the ST are simulated using a single actuator and cable, an angle in between both muscles is considered, based on the vector sum of both simulated muscle forces. Figure 4 shows the updated setup of the UGent knee rig with 1 quadriceps and 2 hamstrings actuators.

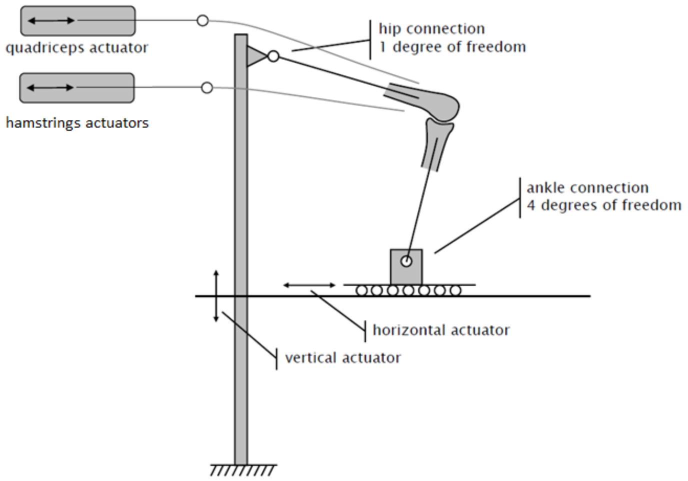

Figure 4 Actuators of the knee rig

The pulleys on which the cables of the actuators run are shown in Figure 5. In this figure, Q indicates the path of the cable used for the quadriceps actuator (as previously shown in Figure 2). The cable runs over the pulley from axis A over D to B. H points to the paths of the cables for both the hamstrings actuators. These cables go from the pulleys on axis A over C to D. The pulleys on axis C are needed to avoid detachment of the cables on the pulleys of axis A during the range of motion.

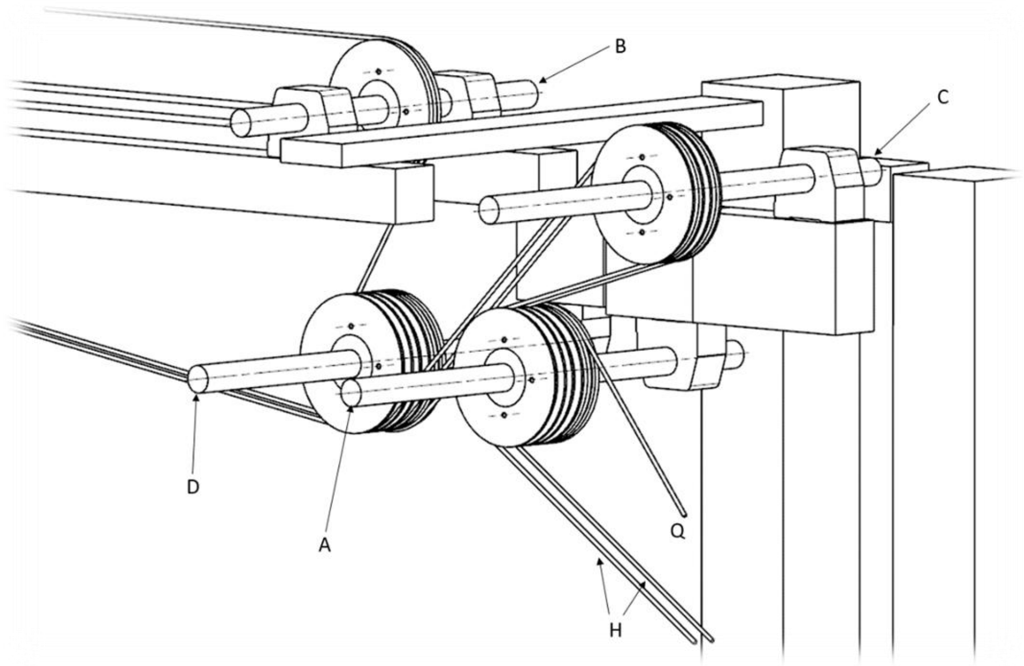

Figure 5 Pulleys and paths

Figure 3 showed that the maximum force of the BF is smaller than that of the SM and ST. Since the sum of these last two forces has to be simulated with one actuator, they determine the maximum power of the actuator. During running a maximum combined force of 2100 N is needed (1400 N for the SM and 700 N for the ST). This was taken as a starting point to select the actuators.

The stroke of the actuators is determined by a combination of factors: the contraction length of the muscles, the strain on the tendons and the angle over which the cable runs on to the pulleys. The contraction length and the angle over the pulleys was simulated using a MATLAB program and, in combination with the maximum strain of the tendons, a maximum stroke of 15 cm was calculated.

4.3 Inverse dynamics

In a dynamic analysis of a mechanism external and driving forces are added to a model and the positions, velocities and accelerations of the components of that mechanism are subsequently calculated. To know the muscle forces during motion, the inverse way of solving a problem is to be used. Starting from a musculoskeletal model that represents a human body and its imposed motion, the muscle forces are calculated in accordance to the (known) reaction forces. This approach is called inverse dynamics and illustrated in Figure 6.

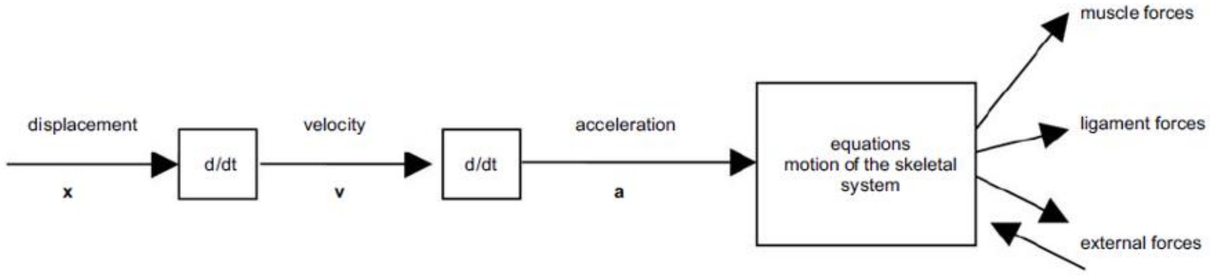

Figure 6 Inverse Dynamics

4.3.1 AnyBody model

The human body is complex and has numerous segments and DOF. That is why specialised software is used to perform the inverse dynamic analysis. More specifically, the AnyBody Modelling System (AMS) will be used. AMS is a musculoskeletal modelling package that uses data from real human bodies and transforms this into a body model.

For the inverse dynamics analysis of the squatting movement, a full body model is used with both feet on the ground. The hip and knee joints are driven and the centre of mass is constrained above the ankle joint.

The cycling movement uses the same body but driven in a different way. A model of a bicycle is added representing the environment. Different parameters are used to determine the motion of the pedals and the exerted forces on the pedals. The models of both bicycle and human body are linked to each other and similar inverse dynamics analysis are performed.

4.3.2 Output processing

The output parameters that are most interesting in this project is the muscle force. This data can be acquired for the different muscle groups and after processing used as input to control the actuators. With this methodology, the amplitude and evolution of the simulated muscle forces will be closer to reality, as they are calculated for each specific motion that is analysed.

5 CONCLUSIONS

The Ghent University knee rig will be equipped with two additional actuators to simulate the muscle forces of the hamstrings. One actuator will be used for the biceps femoris caput longum and the other one for the combination of the semitendinosus and the semimembranosus.

Both actuators need a stroke of 15 cm and a maximum force amplitude of 2000 N. The hamstrings forces are not constant and are determined using musculoskeletal simulations. An inverse dynamics analysis of squatting and cycling is done, resulting in the corresponding muscle forces. These muscle forces serve as input for the actuators' controllers, analogous to the activation of the quadriceps muscles. When the correct muscle forces are known and implemented into the knee rig, the boundary conditions of the rig are updated and their impact to the knee kinematics examined.

6 NOMENCLATURE

Degrees of Freedom - DOF

Biceps Femoris – BF

Semimembranosus – SM

Semitendinosus – ST

Ghent University - UGent

7 REFERENCES

[1] J. P. Goldblatt and J. C. Richmond, “Anatomy and biomechanics of the knee,” *Operative Techniques in Sports Medicine,* vol. 11, no. 3, pp. 172-186, 2003.

[2] T. A. Blackburn and E. Craig, “Knee Anatomy: A Brief Review,” *American Physical Therapy Association,* vol. 60, pp. 1556-1560, 1980.

[3] “ACL Solutions,” [Online]. Available: http://www.aclsolutions.com/anatomy.php. [Accessed 1 December 2014].

[4] “Breaking Muscle,” [Online]. Available: http://breakingmuscle.com/. [Accessed 1 December 2014].

[5] A. B. Zavatsky, “A kinematic-freedom analysis of a flexed-knee-stance testing rig,” *Journal Of Biomechanics,* vol. 30, pp. 277-280, 1997.

[6] E. S. Chumanov, B. C. Heiderscheit and D. G. Thelen, “Hamstring Musculotendon Dynamics during Stance and Swing Phases of High-Speed Running,” *MEDICINE & SCIENCE IN SPORTS & EXERCISE,* 2011.

[7] D. J. Newham, G. McPhail, K. S. Mills and R. H. T. Edwards, “Ultrastructural changes after concentric and eccentric contractions of human muscle,” *Neurological Sciences,* vol. 61, pp. 109-122, 1983.

[8] J. McLester and P. S. Pierre, Applied Biomechanics: Concepts and Connections, Yolanda Cossio, 2008.

[9] W. Mesfar and A. Shirazi-Adl, “Knee joint mechanics under quadriceps–hamstrings muscle forces are influenced by tibial restraint,” *Clinical Biomechanics,* vol. 21, pp. 841-848, 2006.

[10] E. S. Chumanov, B. C. Heiderscheit and D. G. Thelen, “The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting,” *Biomechanics,* vol. 40, pp. 3555-3562, 2007.