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Augmented Modeling of a Lower Limb Assistant Robot and Human Body

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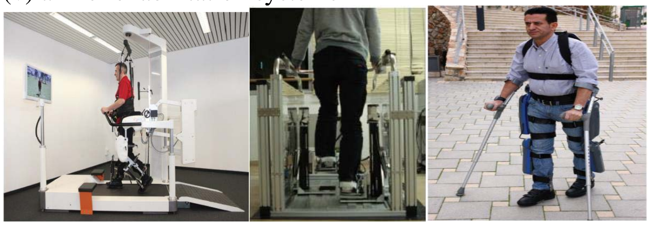
***Abstract*— Rehabilitation robotics is nowadays one of the most attractive fields in robotics. This paper focuses on modeling of a lower limb walking assist device (RoboWalk), augmented with the human body. RoboWalk has been designed to assist either the elderly people or those with malfunctioning in lower limb to do their daily tasks. Modeling the assistive device augmented to human model is highly important for design improvements and controller developments. In such complicated cases, simulators are appropriate tools to analyze the dynamics of robotic devices and understand how the device works which leads to the system improvements. In this paper, a human model that is properly appended to the RoboWalk has been analyzed using the OpenSim software. The human model includes 37 degrees of freedom to define joint kinematics, 80 muscle units actuating the lower limbs, and 17 torque actuators driving the upper body. To this end, the robot has been first added to the human model, then constraints have been properly defined, finally simulation has been implemented by adding a specified gait to human model. Obtained results will be discussed which reveal a reasonable performance of the whole system.**

Keywords- rehabilitation, walking assistant, modeling, OpenSim simulator

I. INTRODUCTION

Increasing number of elder people and aging of society, indicates the necessity of rehabilitation robotics and its crucial role in future life. In past decades, researchers have been seeking for solutions either for assisting and curing disabled people or people with malfunction. Exoskeletons and wearable robotic devices are important fields that have been developed in order to assist people in daily tasks or even cure them. The history of rehabilitation robotics is almost as old as robotics itself. The earliest rehabilitation robots came from the field of prosthetics and orthotics (P&O). The Case Western University arm (1960s) and the Rancho Los Amigos *Golden Arm* (early 1970s) were both adaptations of replacement mechanical arms and are examples of rehabilitation robotic arms [1],[2]. The field of rehabilitation robotics is generally divided into the categories of *therapy* and *assistance robots*. Assistive robots are generally grouped according to whether they focus on manipulation, mobility ,or cognition[1].Over the last decade, several lower-limb rehabilitation robots have been developed to restore mobility of the affected limbs.

These systems can be classified according to rehabilitation principle of the system. (Figure 1): [3]
(i) treadmill gait trainers
(ii) foot-plate-based gait trainers
(iii) over ground gait trainers
(iv) stationary gait trainers
(v) ankle rehabilitation systems



(i)Lokomat system (ii)The GaitMaster5 (iii) ReWalk system wearable

(iv) The Motion Maker (v) Ankle Rehabilitation Robot

Fig.1. Classification of lower-limb rehabilitation robots.

With the mentioned classification some previous works are: the HARDIMAN in 1960 that was a full body powered exoskeleton used for load carrying and developed by General Electric[4],[5], KINEMATIC WALKER in 1969 with two degree of freedom for each leg[4], the ACTIVE SUIT in 1978 actuated with servo motors and controlled with microcomputers[6], SPRING WALKER in 1991, a passive exoskeleton for running with links connected to each other with springs[4], ROBO KNEE in 2004 that allows user to carry load[7], the HAL in 2005 that is a hybrid exoskeleton designed for disabled users[8], BLEEX in 2006 that uses liner hydraulic actuators to reinforce the hip, knee and ankle capable of carrying 75 pound load with 1.3 m/s[9], LOPEZ in 2007 that designed for gait rehabilitation and walking balance[4], MOONWALKER in 2010[10] and REWALK in 2012 for people with spinal injury[11], the KIT-EXO in 2015 with three degrees of freedom[12].In this paper the walking assistant robot that has been designed in previous works based on HONDA weight supporting system will be analyzed using augmented simulation. First the system will be reviewed, then the simulator will be introduced, finally dynamics of human and walking assistant system constrained to each other will be discussed.

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II. TECHNICAL REVIEW

The considered system is a walking assist device that can be put on and taken off easily without the need to fasten the device to a user's body. The basic concept of designing is to keep the assist force vector direction, along the direction from center of pressure of floor reaction force to the center of gravity of the user's body[13] (figure 2), using only two actuator in the upper link that transfers the moments to the knee through a transmission mechanism. In this case, user’s weight or pressure in joints will reduce.

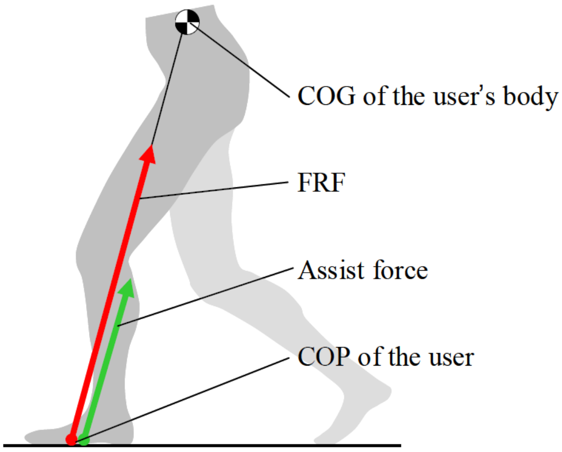


Fig. 2. Design concept on assist force vector.

In the previous works kinematics and dynamics of system have been analyzed, using the analytical solution for device and human in sagittal plane. results have been reported[14],[15]. So we decided to simulate the system with the presence of human and considering the dynamics of the system in order to achieve some valuable results. The system structure is shown in figure 3.

Fig. 3. System structure.

In order to develop the system and choosing motors (actuators) and also design improvement possibilities , we need to calculate the moments needed to be applied to move the system to track a desired motion. By simulating the constrained model, the necessity of physical prototype is lowered and we can achieve valuable information for future works.

III. MODELING

Since the human-robot interaction need to be studied, the OpenSim simulator[16] was chosen to simulate the system. Virtual modeling is a useful tool both for designing step and evaluation of alternatives and even optimization. This is an open-source multibody software developed by Stanford University to create and analyze the musculoskeletal systems, and also kinematics and dynamics simulations of human in order to study the behavior of the system in different conditions.

A. Bodies and joints

In this study, an existing human model with validated data is used to implement the simulation. The human model includes bony geometry for the full body, which includes 37 degrees of freedom to define joint kinematics, Hill-type models of 80 muscle-tendon units actuating the lower limbs, and 17 ideal torque actuators driving the upper body. The model geometry is representing a 75 kg and 170 cm male body[17].
The degrees of freedom of the model can respectively modified and any parameters, can change in the model. Coordinates can be locked during the simulation, and changing the initial pose of human is possible . The first step was to produce CAD parts using a CAD software. Since this is the first simulation, the links are designed simple in order to simplify the simulation. The geometry of the human and simple assistive system is shown in figure 4. As you can see in the next figure, the human lower limb is actuated by a set of muscles (red lines) and the upper limb is actuated by coordinate actuators in software. Important human bones of both upper and lower limb, are shown in figure 4.

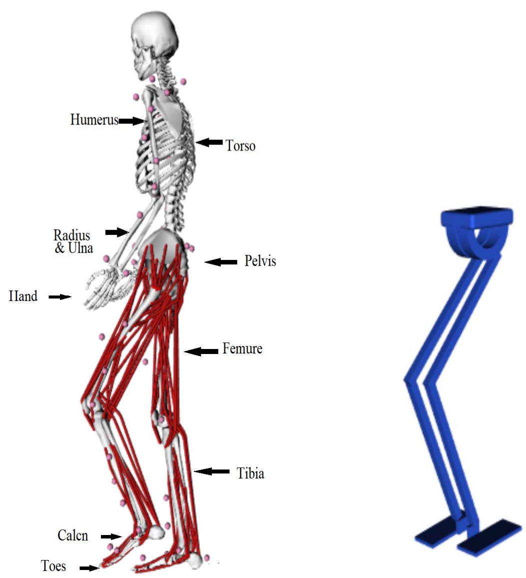


Fig. 4. Human model and assistive system CAD structure

After designing the links, the CAD file including the mass, center of mass and mass inertia added to human model. In this software the connection between the bodies is defined by a parent-child relation. The seat of the assistive device has been connected to the pelvis of the human, two guides has been jointed to seat, the upper links has been jointed to the guides by defining a custom joint that perform the sliding on the curve, the lower links has been jointed to upper links and finally the shoes has been connected to lower links. The topology view of the human model augmented to the assistive device, is shown in figure 5, and specified parameters are shown in table 1.

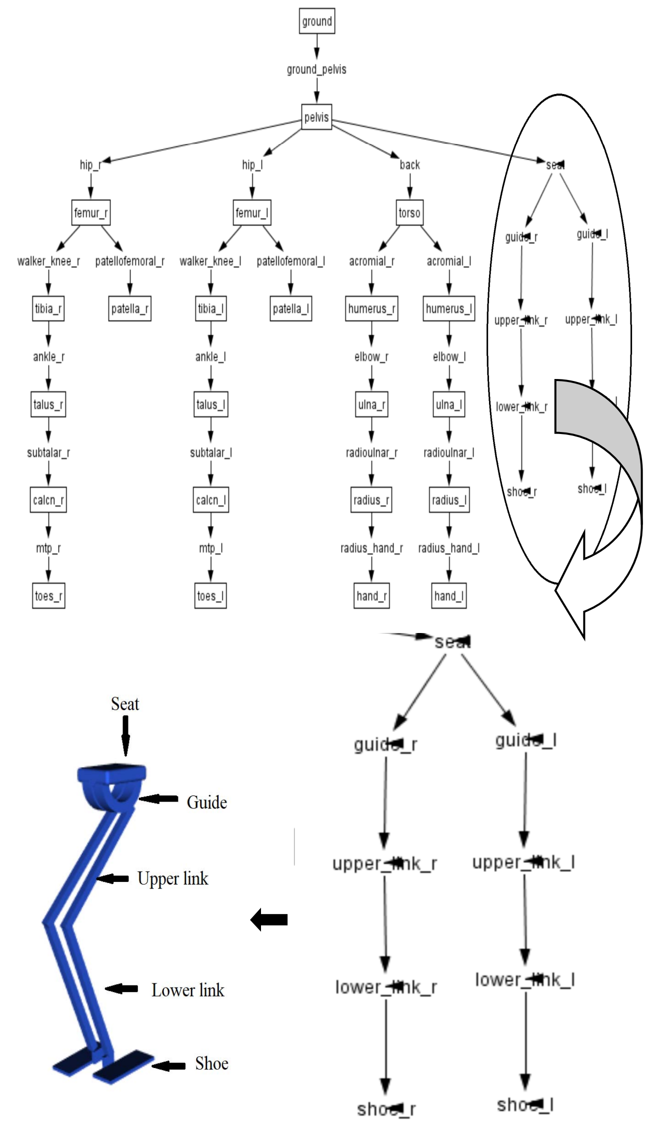


Fig. 5. Topology view of human model augmented to assistive device.

As shown in figure 5, pelvis is the parent body for torso, femur and the seat of RoboWalk. And the other parts are jointed hierarchical to their parents respectively. The important angles for this study are: knee angle that has one degree of freedom, ankle inversion and hip flexion. the other angles and coordinates in lower limb are not as important as mentioned coordinates in our simulation.

For estimating the weights of each component, we can use a material in CAD software for existing dimensions. In this study, final overall weight of assistive device is about 9 kg, which is almost close to the real device. Also the center of mass and mass inertia data of device is collected from CAD software.

Table I. specified parameters of assistive device

Parameters	Mass(kg)	Dimensions(m)
Seat	2.5	0.2*0.05
Guide	1	0.22(d)*0.04
Upper link	0.88	0.42*0.03
Lower link	0.84	0.38*0.03
Shoe	0.4	0.23*0.08

There are deferent types of joints that have been used to define the connections. A *Pin Joint* introduces one coordinate about the common z-axis of the parent and child joints frames. *Pin joints* were used to define the ankle and knee joints. And also the guides rotation is defined by this type of joint. A *Custom Joint* is used to specify 1-6 coordinates and a custom spatial transformation[18]. It was used to define the connection between seat and pelvis and also the slider joints of the hips. The translational function of the slider joint was accurately defined according to the guide radius so the upper link can move on a curve(circular) path. Another type of joints is *weld joint* that does not have any degrees of freedom and will fuses to part to each other.

Another steps in modeling is scaling, which is a tool in software that can modify the parameters of any added model to fit in a desired measure or fit in another model. After the scaling step and constraining (next section), the modeling phase will be completed.

One important consideration in connecting the upper link to the guide is the tangency of this two parts in order to put the assist force aligned to the center of gravity of user. And this contact will remain tangential by rotation of the upper link as shown in figure 6.

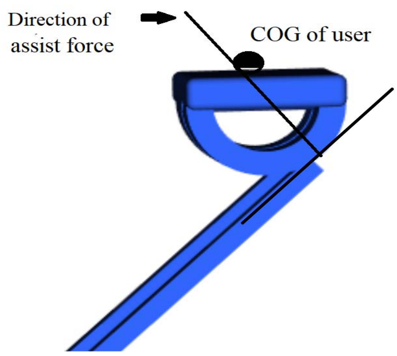


Fig. 6. The tangential contact between upper link and guide.

The seat is simply designed horizontal Since the contact between the seat and pelvis is in a single point. So the real shape of the seat is not important here. Also the transmission mechanism in real device, has been replaced with the knee actuators. A class named *simmspline* has been used to define the translational movement of upper link along the curve path of the guides. This class defines the movement of the upper link in the X & Y direction. The reference frame of the model is shown in figure 7.
After adding the designed parts to human model, defining the joints and scaling the model, the constraints, actuators and any external inputs (such as external load) can be added to the human model.

B. Constraints and actuators

To satisfy the kinematic relation between the device and the system, two types of constraints were used. A *Coordinate Coupler* type constraint was used to couple the motion of the guide and hip adduction (The hip has three DOF including hip flexion, hip adduction and hip rotation). In this walking assistant robot, adduction of hip is same as the rotation of guide. A *Coordinate Coupler & constant distance* type constraint were used to couple the motion of the shoe and foot. by using this two types of constraints the motion of shoe and foot was successfully coupled. The human model augmented to assistive device is shown in figure 7.

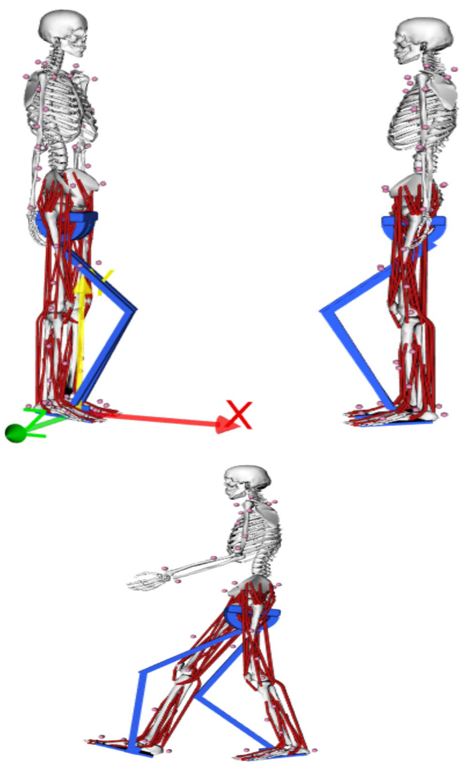


Fig. 7. Human model constrained to assistive device.

In the real assistive device, the actuators are placed in the hip and the generated moments transfers to the knee using a mechanism. We added two actuators in the knee instead of the hip, to satisfy the actuation task in the model. The actuation task can be afforded to actuators. This assumption can be used for users with lower limb disability. In this case the muscles can be deactivated. Since in reality, the actuation task is both by human muscles and robot actuators, in this study muscles are enabled, to compute the actuation task by actuators and muscles together.

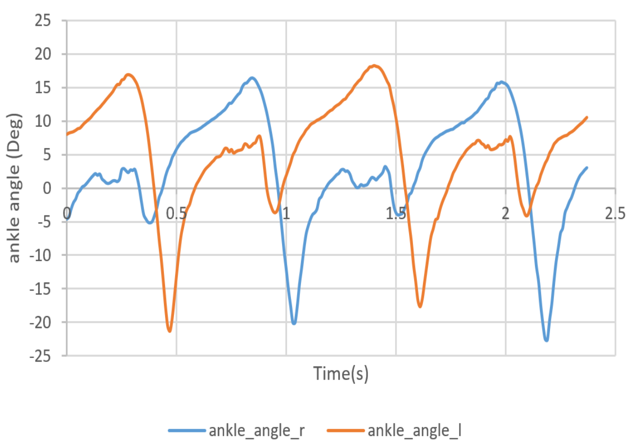
IV. SIMULATION

After modeling phase, the simulation of human and walking assistant device can be implemented. In this case we used a gait cycle of duration 1.4 s. there are deferent tools in the software to analyze dynamics. Inverse kinematics tool is another useful tool that can be used to track any position of any components. The position of assistive device components and any new bodies can be tracked by adding markers and using the mentioned tool. As we mentioned, the motion is imposed to the human model and actuators show the moments, needed to compensate 10 percent of human weight.

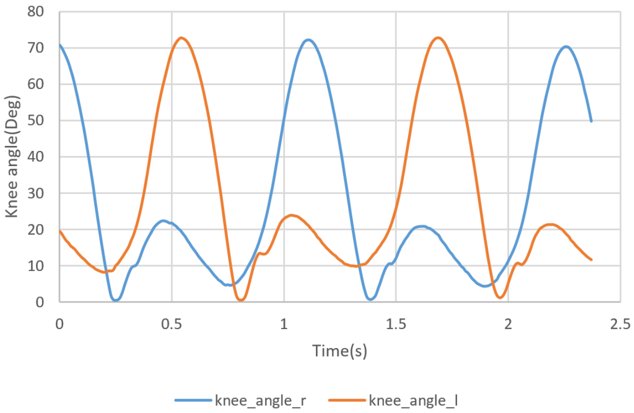
For now the inverse dynamics and Computed Muscle Control(CMC) used to analyze the dynamic of human and constrained human model. The CMC's purpose is to compute a set of muscle excitations (or more generally actuator controls) that will drive a dynamic model to track a set of desired kinematics. The control strategy used by the CMC consists in the combination of a proportional-derivative (PD)controller and a static optimizer[18].

V. RESULTS

The position of knee and ankle of human model are shown in figure 8.



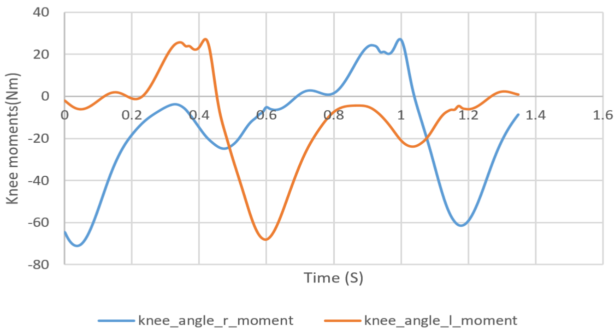
(a)



(b)

Fig. 8. The position of human a)ankle b)knee

The moments of human knee, ankle and hip using a desired gait, are shown in figure 9.



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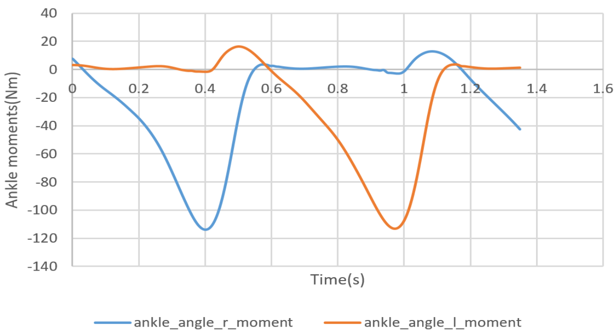

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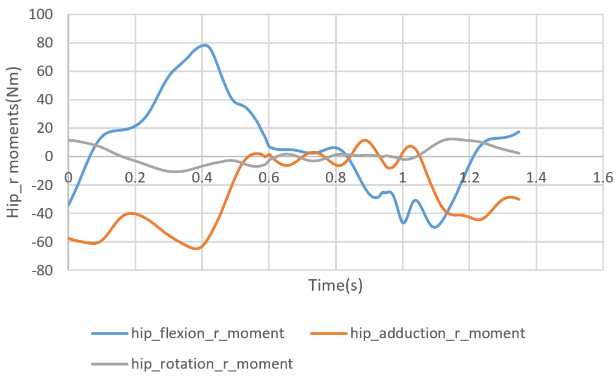
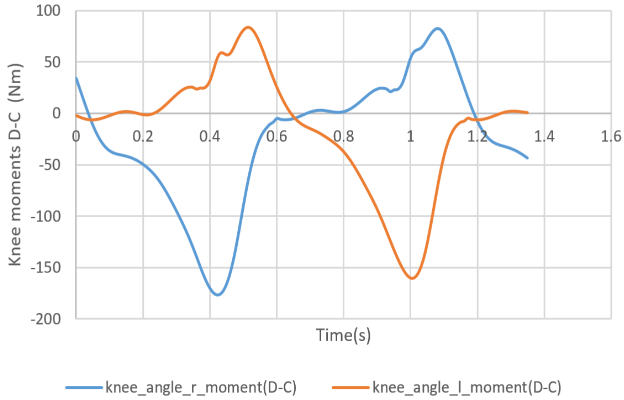


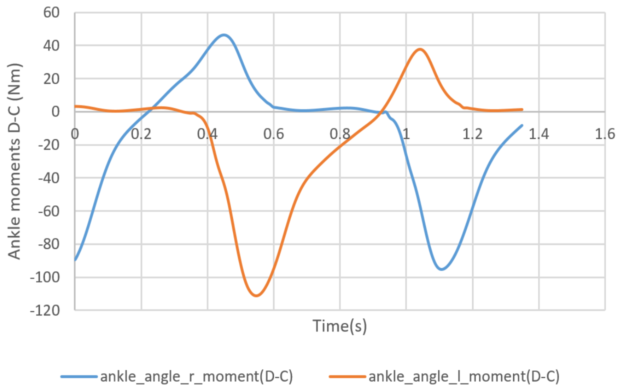
(c)

Fig. 9. The moments of a) knee b)ankle c)hip of human model.

The knee and ankle moments of human constrained(D-C) to assistive device are shown in figure 10.



(a)



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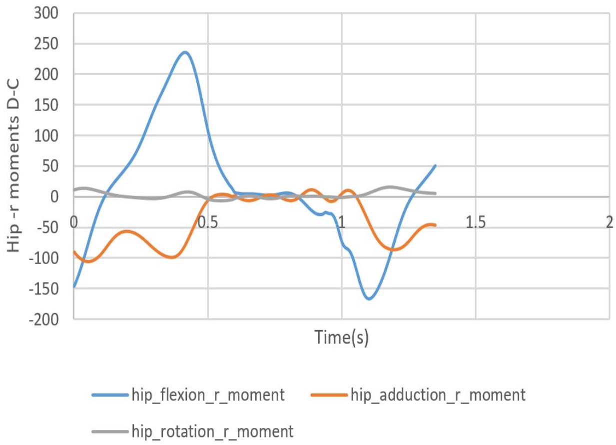

(C)

Fig. 10. The moments of a) knee b)ankle c)hip of human Model constrained to assistive device.

And the knees actuation moments of assistive device are shown in figure 11. As we mentioned, the purpose of the simulation is to compensate a portion of human weight by applying the assist force to COG.

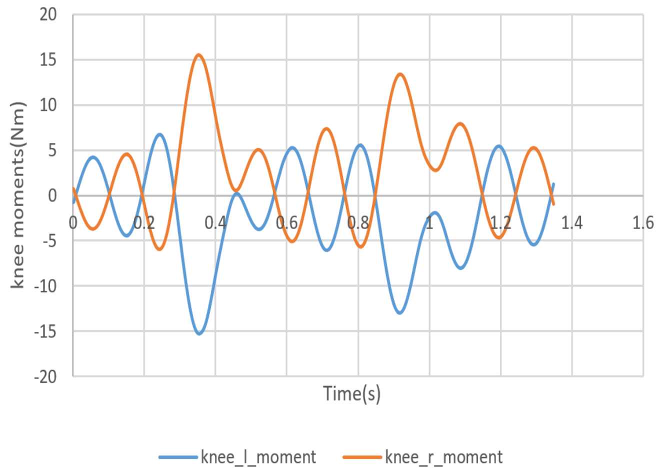

Fig. 11. The knees actuation moments of assistive device.

VI. CONCLUSION AND FUTURE WORKS

A lower limb walking assistant robot constrained to human body model was simulated in a biomechanical simulator called OpenSim to analyze the dynamics and considering the behavior of the whole system. After adding the assistive device model to human, a desired gait cycle of walking imported to model and the simulation implemented and results reported. The presence of the assistive device can help users by reducing the pressure in deferent parts of the body. As the assistive device has some challenges, studying the performance of the device augmented to human model can help us to improve the ability of the whole system. Adding actuators and revising the design, are examples of tests that can lead to improvement.

Comparing the results with real device to verify the results and also developing a ground contact model would be interesting. Considering control strategies in the software and also optimization of the properties to improve the accuracy of modeling, are examples of future works.

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