Observations of human muscle response during daily life activities of biped kinematics using a musculoskeletal simulator

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Abstract: *Research in biomechanics has numerous applications including rehabilitation which helps in the fabrication of assistive devices. The Assistive devices or exoskeletons are used to serve the patients affected by stroke and spinal cord malfunctioning. These devices are programmed to follow a fixed redundant gait cycle and are lacking in producing natural movement of the gait. To overcome this limitation and make the device more user comfortable during usage of their daily life activities, a thorough study was done using an open source software that contributed to the design of exoskeleton device for the subject. In the current study, a simulation of various daily life activities are thoroughly studied using a musculoskeletal simulator package like OpenSim. The paper presents the observations of muscle responses from ground reaction forces with minimized metabolic cost function in various activities of daily living such as sitting to standing, standing to sitting, jumping, twisting suddenly while walking and turning suddenly. The study deliberates the inputs for developing more comfortable exoskeletons in performing tasks in a more sophisticated manner.*

Key Words: *Daily life activities, Musculoskeletal modeling, Simulator, Muscle response, Ground reaction force*

1. INTRODUCTION

The study of human muscle is coined for the development of assistive devices and other medico-surgical issues. Most of the case studies are presented to design and develop an exoskeleton that is user friendly. Since the beginning of exoskeleton devices [1] in 1965, these devices have been transformed in terms of user flexibility [2] and comfort [3]. The cost function such as the metabolic cost is also reducing with the increase in complexity of the devices [4]. Certain biomechanical experiments [5] about specific activities are mentioned to study the responsiveness of muscles that are studied through the OpenSim [6] musculoskeletal (MS) simulator, which is an open-source product. This tool is equipped with unified multibody dynamics [7] with human muscle simulation code. Simulation-based studies are useful in the design and analysis of the exoskeleton parameters and kinetics & kinematics of the user [6]. This system consists of rigid skeletal structures that together with the muscle and the constraint function are similar to a normal human being. The extended OpenSim model is used for the analysis of connective tissues [8]; it provides experimental data that are impossible to obtain by simulation. In a comparison of the OpenSim standard MS model with the scaled model, the inverse kinematic weights at appropriate makers positions of high values result in acceptable remarks in the literature of the stream. Finally inverse kinematics (IK) makes the considered model validated with the experimental values as well as the mathematical empirical relations. The joint impairments [9] due to improper alignment of exoskeleton or assistive devices can be determined by the tool. Locomotion assisting devices are proposed to reduce the burden of muscles during activity, this reduction may be either usage of motors in active devices or may be no active torque in case of passive devices. The performances of this kind of devices are usually rated by their metabolic cost, and the one which provides less rating is an ideal device. The present work attempts to study the various biomechanical activities of daily life (ADL) such as gait, sit-to-stand & stand-to-sit, jumping, sudden twist during gait, sudden turning activities.

2. METHODOLOGY

Modeling and simulation musculoskeletal structures are carried out in OpenSim 4.0. The code of the 3D Gait Model 2392 is used which is a 23 DOF, 92 muscle components with 13 rigid segments, imported for the study. During the simulation, certain assumptions are followed by the predefined functions of the simulator system.
The outline of the study is shown below:

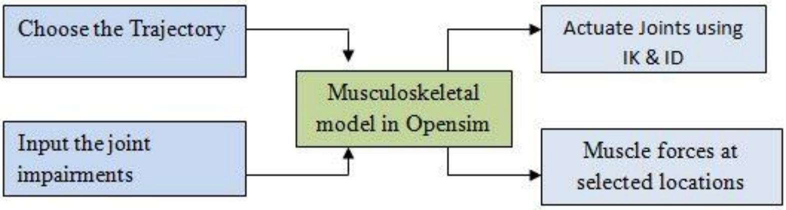

Fig. 1 – Outline of the work

Knee plays a vital role for all the fore-mentioned activities for the observation; it is noticed that the quadriceps are responsible for the extension, whereas hamstrings are responsible for flexion of the knee which consists of RF (Rectus Femoris), VI (Vastus Intermedius), ST (Semitendinosus), VM (Vastus Medialis), biceps femoris (Small & Large) muscles.

3. KINEMATIC SYNTHESIS

Biomechanics research requires the data of human body such as angle movement along with the constraint condition of joints, the change of positions within the workspace. These data can be made available by motion capture technology with or without using markers; most commonly used motion capture software adopts geometric approach. In this approach, angles are determined by trigonometry. In the present work, an OpenSim model 3DGaitModel2392 is used for the study. In the case of dynamic walking the trajectories of the foot in both planes i.e., coronal and lateral planes are approximated by cubic splines [10].

$$P = C_0 + C_1x + C_2x^2 + C_3x^3 \tag{1}$$

$$P' = C_1 + 2C_2x + 3C_3x^2 \tag{2}$$

$$P'' = 2C_2 + 6C_3x \tag{3}$$

$$P''' = 6C_3 \tag{4}$$

4. COMPUTATION AND MATHEMATICAL MODELLING IN OPENSIM

Joint coordinates are attained by inverse kinematics (IK), whereas Inverse Dynamics (ID) is used to compute the joint torques and ground reaction forces from the fed data of kinetics & kinematics related to the activity to be performed. ID results in generalized forces for all the joints in a simple way. However, it comes with some constraints like uncertainties in segmentation, data collection from force plate, processing of kinematic data etc. OpenSim adopts two methods; one is to measure muscle activation levels and the other one is the muscle excitation rate as CMC (Computed Muscle control). The conditions for the movement of a musculoskeletal model are given as:

$$M(\dot{qi}) + N(qi, \ddot{qi}) + \tau_d = \tau \tag{5}$$

q_i	position variable vector.
$\dot{qi}$	variable of displacement
$\ddot{qi}$	variable of acceleration.
M	mass matrix.
τ_d	torque vector with uncertainty.
τ	the forces applied externally.

The equation of motion, is postulated by the conditions below [11-12] .

$$\sum_{i=1}^{n_i} (a_i F_i^0) r_i, k = \delta k_i \tag{6}$$

$$\sum_{i=1}^{n_i} [a_i f(F_i^0, l_i, v_i)] r_i, k = \delta k_c \tag{7}$$

The minimum cost function is given by

$$\boldsymbol{C} = \sum_{i=1}^{n_i} (a_i)^p \tag{8}$$

where

n_i	is the number of active muscles in the model,
a_i	is the level of muscle activation,
l_i	is the fibre length active muscle,
r_i, k	is the active muscle moment, and arm force about joint axis of k,
v_i	is the active muscle of shortening speed,
$f(F_i^0, l_i, v_i)$	is the function of force length- velocity criterion,
k_i	is the ideal force generators torque,
k_c	is the force length torque constrained parameters.

The considered objective function for optimization is calculated by inverse kinematics solver of the simulator considering the appropriate penalty parameter and the expression is given by

$$z = \gamma \sum_{t=0}^{N} \left[\sum_{i \in \forall} w_m \left\| x_{im}^{exp}(t) - x_m(t) \right\|^2 \right]^2 + \delta \sum_{t=0}^{N} \theta_t^2 (t) \tag{9}$$

where γand δ are weighting factors, respectively, $\boldsymbol{x}_{\mathrm{m}}\exp(t)$ is the experimental marker position, $\boldsymbol{x}_{\mathrm{m}}(t)$ is the respective model marker, wm is the marker weight, $\theta p\ (t)$ is the tilt in radians with respect to a neutral standing position at time t, and N is the total number of time intervals.

Table 1 - Model configuration considered and its corresponding inverse kinematic weights

S. No.	***Marker position***	***Scaling***	***IK weight***	***IK Tracking***
1	Sternum	No	1	Yes
2	RIGHT Acromium	No	1	Yes
3	LEFTAcromium	No	1	Yes
4	Top.Head	Yes	1	Yes
5	RIGHTASIS	Yes	20	Yes
6	L.ASIS	Yes	20	Yes
7	R.PSIS	Yes	20	Yes
8	L.PSIS	Yes	20	Yes
9	LEFTIliac.Crest	Yes	1	Yes
10	V.Sacral	Yes	1	Yes
11	RIGHTThigh.Upper.Post	No	20	Yes
12	RIGHTThigh.Upper.Ant	No	20	Yes
13	RIGHTThigh.Lower.Ant	No	20	Yes
14	RIGHTThigh.Lower.Post	No	20	Yes
15	RIGHTKnee.Lat	Yes	1	Yes
16	RIGHTShank.Upper.Post	No	20	Yes
17	R.Shank.Upper.Ant	No	20	Yes
18	R.Shank.Lower.Ant	No	20	Yes
19	R.Shank.Lower.Post	No	20	Yes
20	Right.Ankle.Lat	Yes	1	Yes
21	Right.Heel.Upper	Yes	1	Yes
22	Right.Heel.Med	No	20	Yes
23	Right.Heel.Lat	No	20	Yes
24	Right.Toe.Lat	No	20	Yes
25	Right.Toe.Med	No	20	Yes
26	Right.Toe.Tip	Yes	1	Yes
27	Left.Thigh.Upper.Post	No	20	Yes
28	Left.Thigh.Upper.Ant	No	20	Yes
29	Left.Thigh.Lower.Ant	No	20	Yes
30	Left.Thigh.Lower.Post	No	20	Yes
31	Left.Knee.Lat	Yes	1	Yes
32	Left.Shank.Upper.Post	No	20	Yes
33	Left.Shank.Upper.Ant	No	20	Yes
34	Left.Shank.Lower.Ant	No	20	Yes
35	Left.Shank.Lower.Post	No	20	Yes
36	Left.Ankle.Lat	Yes	1	Yes
37	Left.Heel.Upper	Yes	1	Yes
38	Left.Heel.Med	No	20	Yes
39	Left.Heel.Lat	No	20	Yes

40	Left.Toe.Lat	No	20	Yes
41	Left.Toe.Med	No	20	Yes
42	Left.Toe.Tip	Yes	1	Yes
43	Cervical.Spine	No	1	Yes

5. STANDARD PROCEDURE FOR METABOLIC COST

1. Importing and modifying the musculoskeletal model
2. Importing musculoskeletal model & integrate with a human model
3. Importing motion capture data & integrate with the kinematic data as per gait
4. Importing the GRF(Ground reaction forces) & ID for torque computing
5. Computed muscle control to generate muscle driven gait simulation
6. Probing the metabolic gain into energy consumption.

6.TOPOLOGY VIEW OF THE MODEL

The cause and its effect of actions on the entire system can be easily identified by Opensim model. For instance, one can identify the changes in the output of simulation on a 3D visualizer by altering the input variables in the GUI of OpenSim. Topology view is a tree diagram that represents a rigid body of the model. Each branch of a tree represents a joint to execute and analyze simulations. Originating from the ground and immediate pelvis that connects the femur and tibia via knee up to toes as shown in the tree diagram.

7. TOPOLOGY VIEW & ACTIVITIES CONSIDERED FOR OBSERVATION

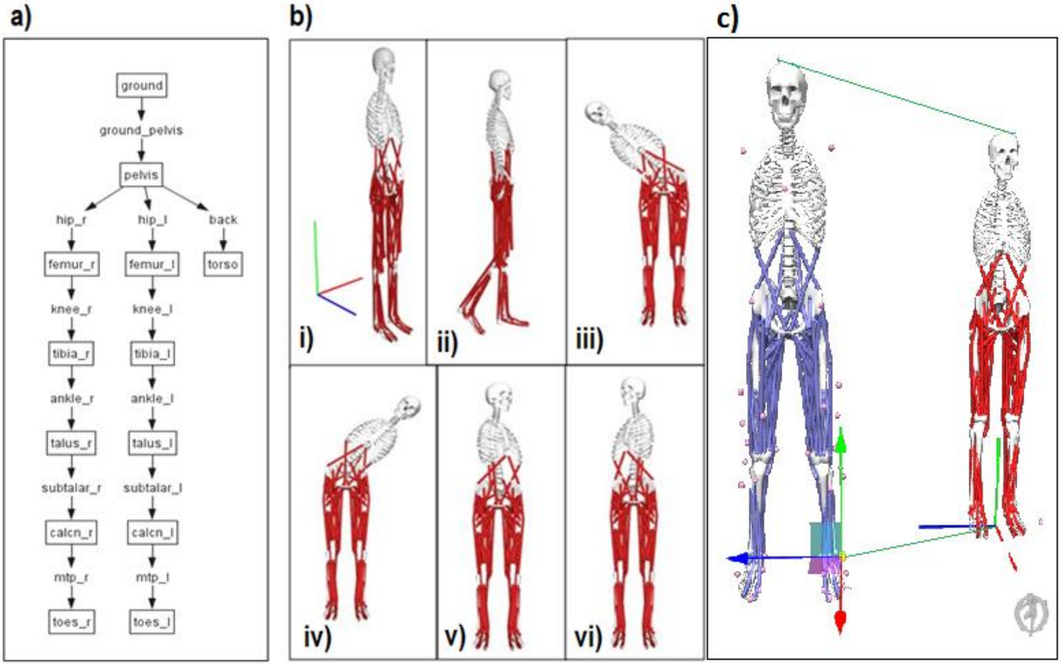

Fig. 2 – a) Topology view of the model; b) OpenSim model Gait239 with actions;
c) Scaled model of weight 72.5 kgs to 75.5 kgs subject considered for caculation of Inverse kinamatics

8. RESULTS & DISCUSSIONS

To correlate the muscle activity with the movements generated, complicated dynamic systems have various complex problems, such as a greater degree of freedom of the anatomical structure of the model and the problem of muscle redundancy. These limitations can be addressed in more detail and can generate a better biomechanical visualization using simulation, instead of analyzing data from the markers directly in OpenSim. The estimated ground force reactions are validated with the aforementioned theoretical relations, as well as with the previous works of various researchers. The vertical GRF varies from heel-strike to toe-off of a similar footand itisn't extremely articulated as normal gait, which can be ascribed to the way that lower leg point is kept consistent in the model to keep away from the complexity of displaying the turnover and stacking reaction activity of the human foot.Hence, most of the exoskeleton designs come with hindrance to ankle variation. Similar muscle force pattern is observed over the normal gait cycle. The cost function associated muscle activity is dependent on several muscles and their level of straining in performing the activity.

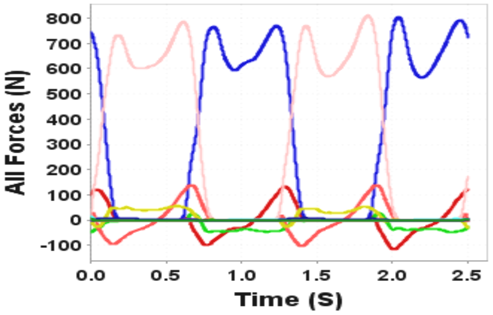

Fig. 3 – Plot of Ground reaction forces versus Time

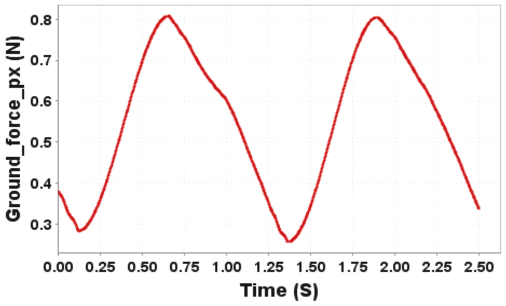

Fig. 4 – Plot of Ground reaction force in X-direction

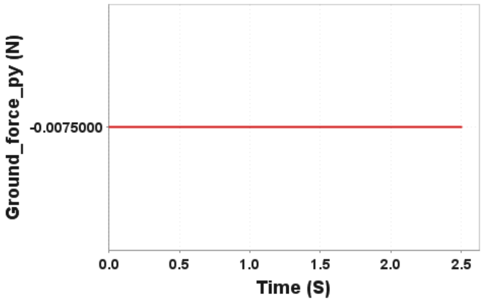

Fig. 5 – Plot of Ground reaction force in Y-direction

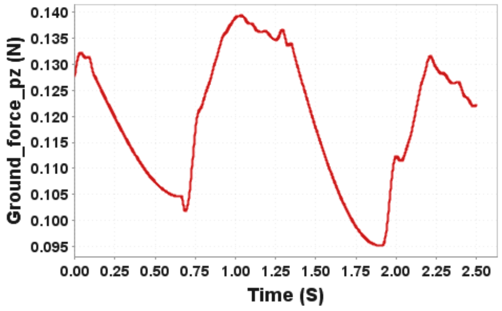

Fig. 6 – Plot of Ground reaction force in Z-direction

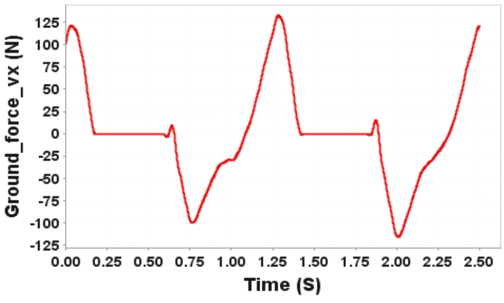

Fig. 7 – Plot of Ground force in X-direction

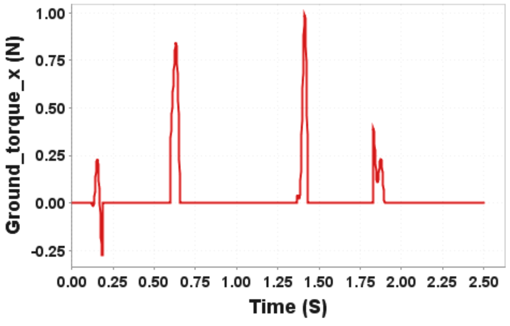

Fig. 8 – Plot of Ground reaction torque in X-direction

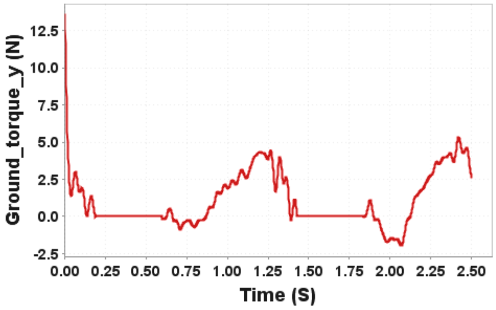

Fig. 9 – Plot of Ground reaction torque in Y-direction

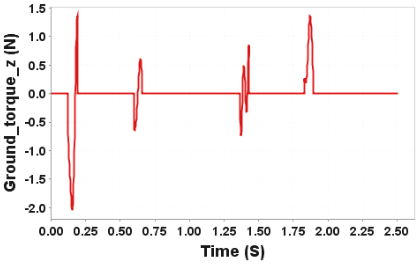

Fig. 10 – Plot of Ground reaction torque in Z – direction

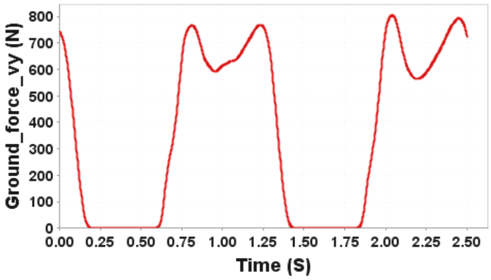

Fig. 11 – Plot of Ground force in Y-direction

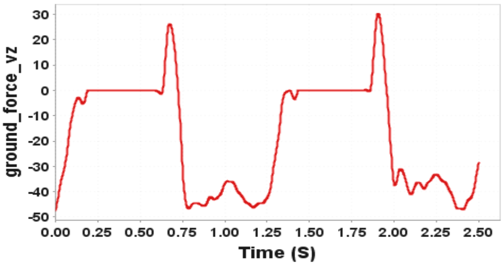

Fig. 12 – Plot of Ground force in Z-direction

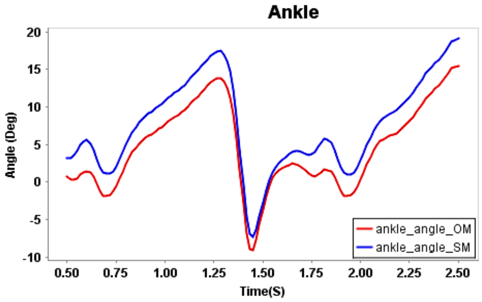

Fig. 13 – Plot of Ankle kinematics in anatomical planes

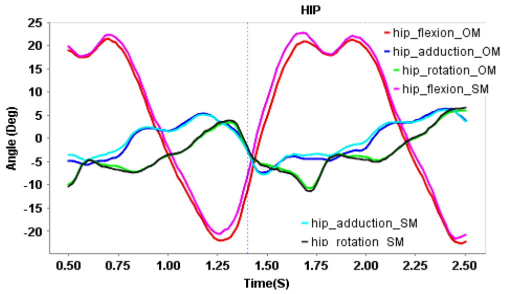

Fig. 14 – Plot of Hip kinematics in anatomical planes

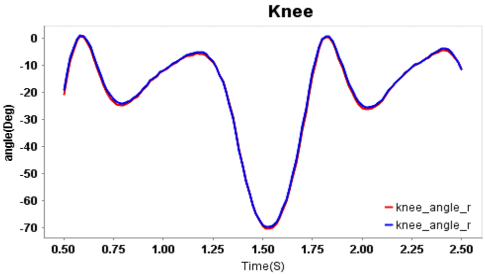

Fig. 15 – Plot of Knee kinematics in anatomical planes

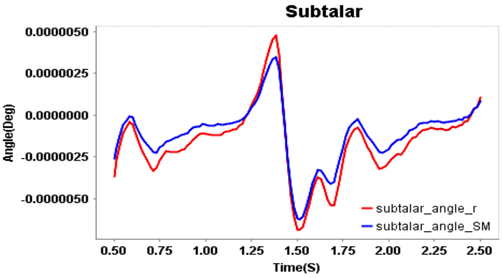

Fig. 16 – Plot of Subtalar kinematics in anatomical planes

As the inverse kinematic weights of the model increases the angle of movement in the sagittal and transverse planes i.e anatomical planes also increase which can be observed from the plotted results of Fig. 3 - Fig. 16, in which the responsive curves of the Orignal Model (OM) superimpose over the Scaled Model (SM) where the point of marker placement and weights increment are carried out. The responsive curves have no effect if both model curves are overlapped.

9. CONCLUSIONS

From the results obtained, it can be concluded that, the ground reaction forces and torque variations are dissimilar with each other with the action performed. More importantly, it can be seen that the ground reaction forces are greater than the mathematical relations considered. The observations made in this study are very useful in the synthesis and design of exoskeleton devices. Therefore in the design of assistive devices priority should be given to the level of user comfort rather than the use of complex repetitive scheduled tasks, however user adaptability is still progressive and intentional prior to research.

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