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A NEW LOWER EXTREMITY MODELING OF HUMAN BODY WITH VARIABLE FEET LINKS

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ABSTRACT

Human movement modeling has been the object of much research for the past 30 years. In these models the position of foot link was fixed on the ground.

We propose to model the feet links as variable, since the position of foot pressure center changes from heel to toes. The ground reaction forces could also be analyzed in real time. We examined this model for some static postures.

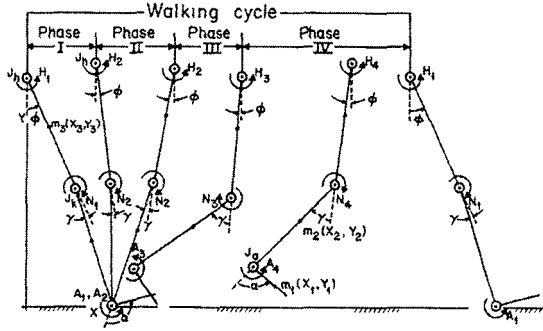
In standing anatomical position, the maximum articular forces are localized in hip and knee joints. In sagittal plane, the ground reaction force vectors are positioned nearly under ankle joints.

The pathological postures like body with pes cavus or with global spine kyphosis increase the articular and muscular

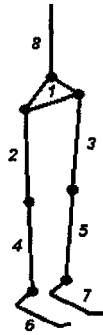
forces. In these cases, the position of ground reaction force vectors is moved toward the toes.

INTRODUCTION

One of the factors in optimization of energy could be minimizing the ground reaction forces. Krab et al. [1] mentioned that improper loading on tibiofemoral joint could be the reason of some injuries. Hume and Gerrard [2] showed that the protection of ankles during sportive activities not only increases their resistance, but also modifies the ground reaction forces. Bobbert et al. [3] analyzed the effects of the shoes on vertical ground reaction forces. They indicated that it is useful to calculate the ground reaction forces.



a- Feet links are fixed on the ground, some where on the heel or on the toes [4].



b- Koopman et al. [5] considered the ground reaction forces as unknown. They defined the feet links with some rigid curves (links No. 6 and 7).

Fig. 1- Examples of the models in the literature.

The movement modeling of lower extremity of body has been the object of many researches. The models were proposed with different degrees of complexity, using between 3 [6] and 17 links [7]. In most of these models, the ground reaction forces were considered as known values of system [8]. In these models the feet positions were fixed on the ground (Fig. 1). This method could not be completely satisfactory, especially in the bipedal models [9]. In reality, feet pressure center changes continuously, from heel to toes.

We propose an original modeling, in which the feet lengths are variable (Fig. 2). This modeling permit us to analyze the position vectors of the feet links, as well as the vectors of the ground reaction forces, in real time.

Assuming that we have already all the articular and muscular forces (which were considered as the only torque generators), the equation system of model stays undefined. We know neither the values nor the positions of the ground reaction forces (12 unknown for only 6 equations of equilibrium). Transferring all the muscular forces to the proximal joint of each link, and separating the feet segments from the model (Fig. 4), we resolved this problem [10].

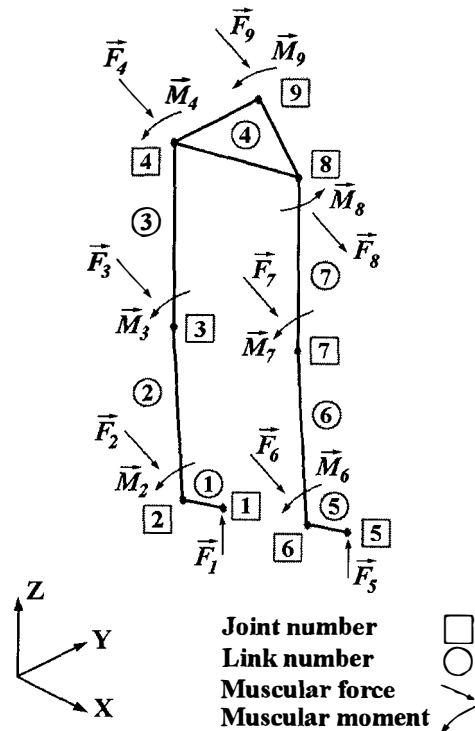


Fig. 2- Lower extremity modeling with variable feet links.

MATERIALS AND METHODS

BIOMECHANICS OF MUSCLES AND TENDONS

Using the force-length ($f-l$) and force-velocity ($f-v$) curves, we defined the passive and active characteristics of muscles. Normalization of these curves permitted us to use them for all of the muscles [11]. These curves are valuable for some defined stimulation. We used the maximum stimulation.

The tendon activities were defined by their mechanical normalized characteristic curves. These curves which are

valuable for most of the tendons, should be modified for some particular ones (ex. tendon of Achilles).

MUSCULO-SKELETAL MODELING FOR LOWER EXTREMITY OF BODY

We modeled the lower extremity of body with seven links (Fig. 2). All the links are considered as rigid materials [12].

The hip segment was defined as a triangle. We considered the upper extremity of body and hip as one unique mass. The center of gravity of this mass was defined as the top of this triangle. Thighs and legs were defined by rigid links.

We modeled the feet segments, with variable links. The ground reaction forces were also calculated.

In this model, we defined the origin and insertion position of 33 muscles of lower extremity of body. For creating our anatomical databases for muscular insertion points and rotation centers of joints, we used the values found in the literature [13]. We modified these values in some cadaveric study.

To prepare the system for Kinematics analysis, we defined the position vectors of muscular insertion points, and the center of gravity of each segment, due to its proximal joint.

All of the articulations, as well as the contact point of feet links on the ground, were modeled by the joints with three degrees of freedom. Except the contact joint of feet links on the ground, friction was neglected in all other joints. The ligaments and cartilages functions, as well as lubrication phenomenon were neglected too.

KINEMATIC ANALYSIS OF SEGMENTS

The forces and moments affected on each member could be represented by schematic Fig. 3. A Hill type model, associated with an iteration algorithm, was used to analyze the muscular forces.

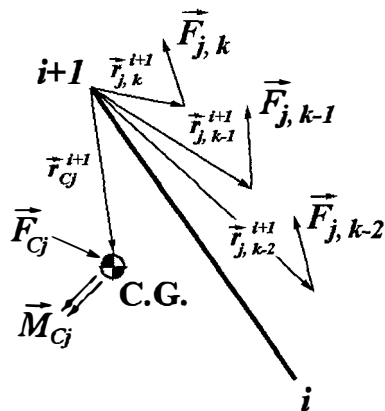


Fig. 3- The forces and moments effected on some assumed link.

We transferred all the forces and moments of each segment to its proximal joint. They could be analyzed by the following equations:

$$\vec{F}_{i+1} = \vec{F}_{cj} + \sum_{m=1}^k \vec{F}_{jm} \quad (1)$$

$$\vec{M}_{i+1} = \vec{M}_{cj} + (\vec{r}_{cj})_{i+1} \times \vec{F}_{cj} + \sum_{m=1}^k (\vec{r}_{j,m})_{i+1} \times \vec{F}_{j,m} \quad (2)$$

i : joint number, j : link number, k : number of muscles which are inserted on ' j ' th link, $C.G$: link center of gravity, Cj : center of gravity indice, \vec{F}_{i+1} : sum of muscular forces which are transferred to the proximal joint, \vec{F}_{cj} : inertial force, \vec{F}_{jm} : muscular forces effected on link, \vec{M}_{i+1} : sum of muscular moments after transferring the muscular forces to the proximal joint, \vec{M}_{cj} : inertial moment, $(\vec{r}_{cj})_{i+1}$: position vector of the center of gravity of link due to its proximal joint, $(\vec{r}_{j,m})_{i+1}$: insertion point position vector of some muscle attached on the link due to its proximal joint.

The equation system of the general model shown in Fig. 2 is undefined. To resolve this system, we divided it to three sub-systems (Fig. 4).

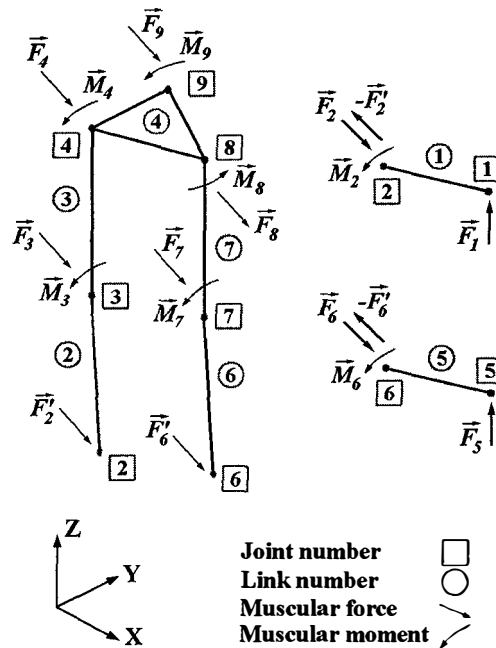


Fig. 4- Division of global model to three sub-models.

First of all, we separated the feet segments from general model. The forces and moments of ankle joints, in the general model, are the effects of the muscles inserted on feet segments. They could be easily transferred to the proximal joints of the separated feet links. We must only add some articular forces to the ankle joints of the sub-systems.

Now, we have three sub-models with defined equation systems. Analyzing the body sub-model for ankle articular forces (\vec{F}'_2 and \vec{F}'_6 in Fig. 4), we can calculate the feet sub-models to find out the vectors of the ground reaction forces (as well as the length and position of each feet link).

RESULTS

To validate our model, we carried out some analysis for static postures.

STANDING ANATOMICAL (NORMAL) POSTURE

The model of anatomical posture was shown in Fig. 5a. Even in static posture we can observe the muscular contraction (Fig. 6). The muscles are the principal elements for body equilibrium.

The maximum values of articular forces are localized in hip and knee joints (Fig 7). The ground reaction force is situated nearly under ankle joint (Fig. 5a, down).

EXAMPLE FOR FEET WITH PES CAVUS

Comparing the models of body with pes cavus (Fig. 5b) and normal position of body, we notify some increase of muscular contraction in almost all of the muscles (Fig. 6). It causes an increase of articular forces (Fig. 7). The ground reaction forces are moved. They could be observed near middle of the feet (Fig. 5b, down).

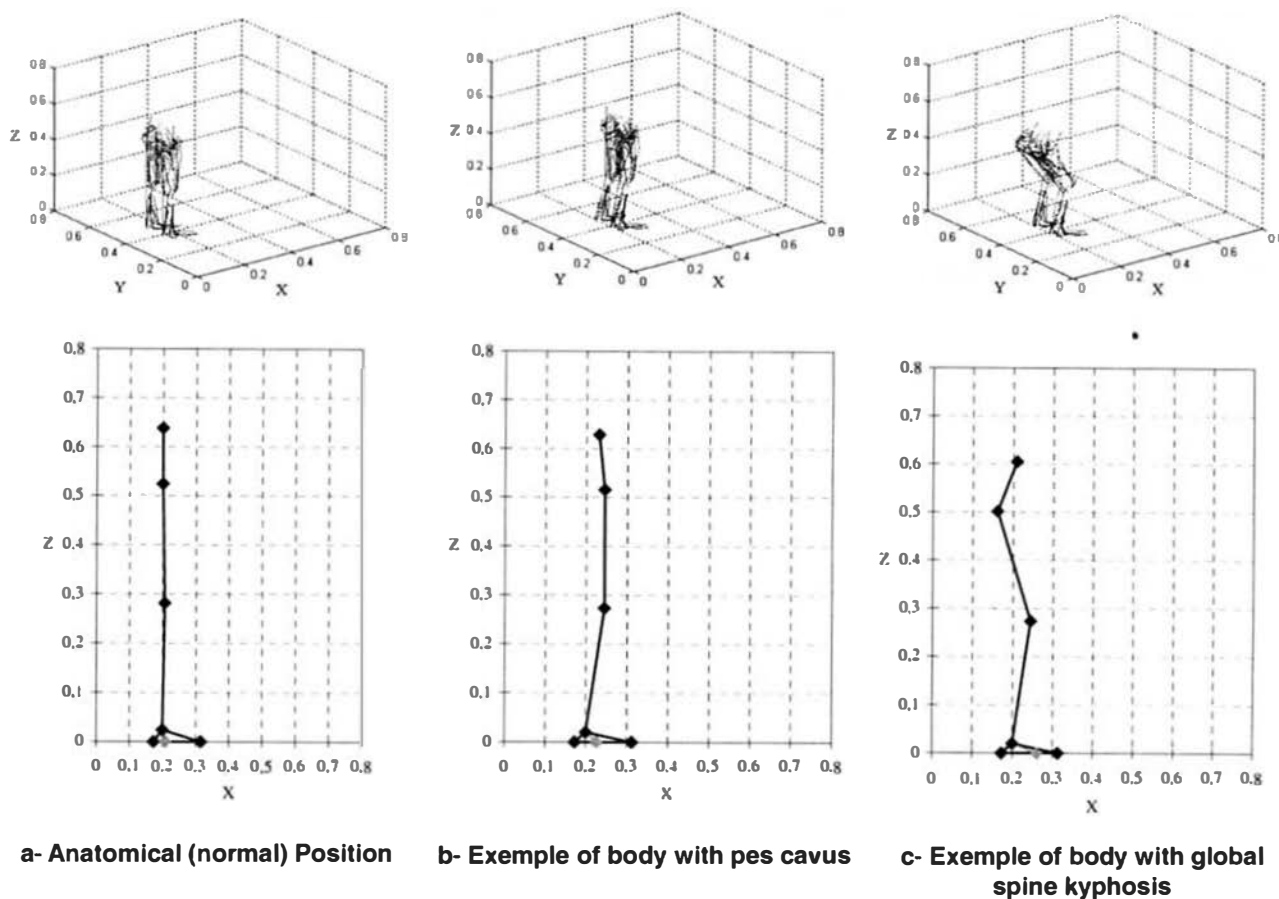


Fig. 5- Modeling of Lower extremity of body for different static postures. (Up : Musculo-skeleton models; Down : articular positions; All the models are normalized with body height)

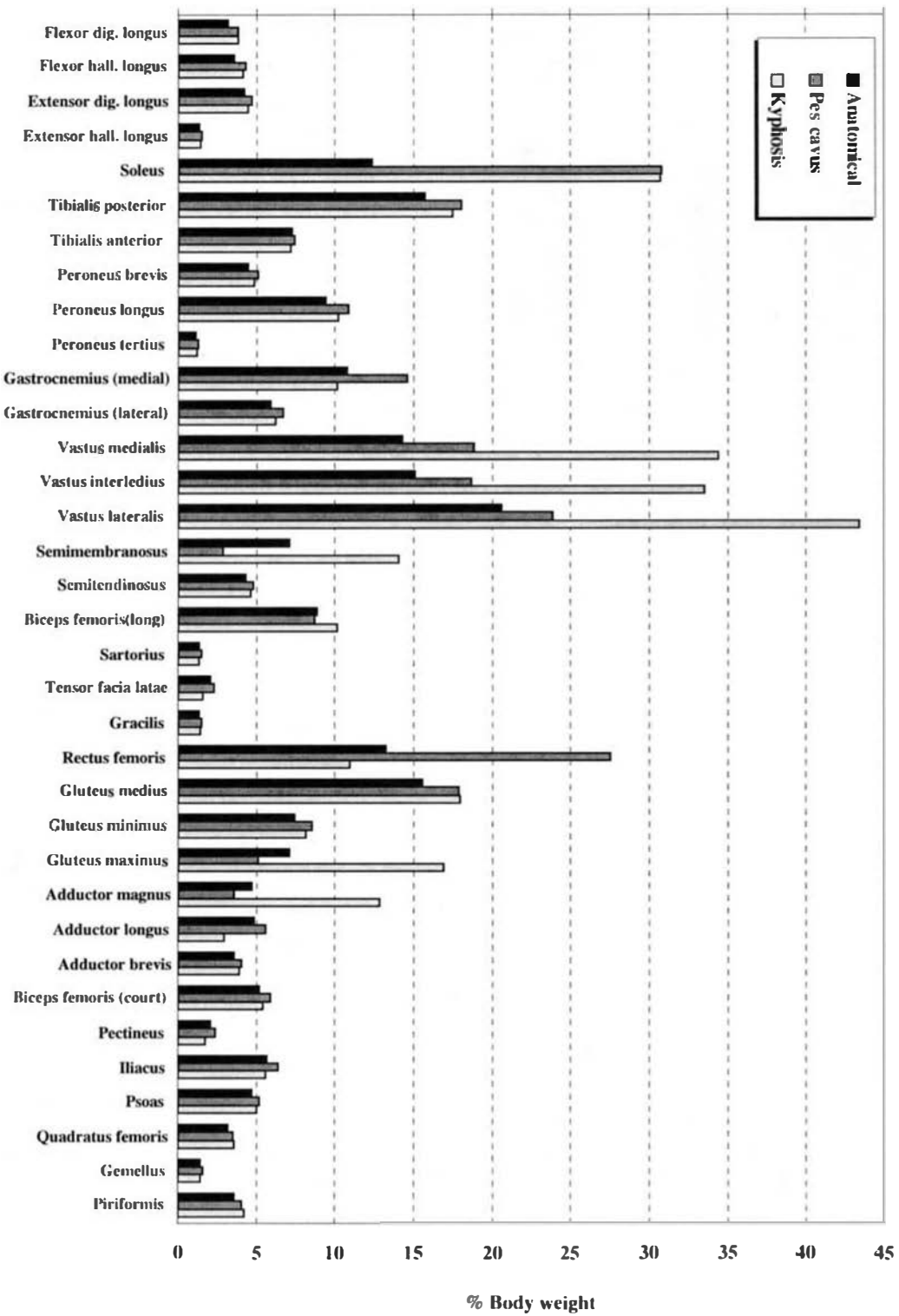


Fig. 6- Comparing the muscular forces of lower extremity of body for different static postures

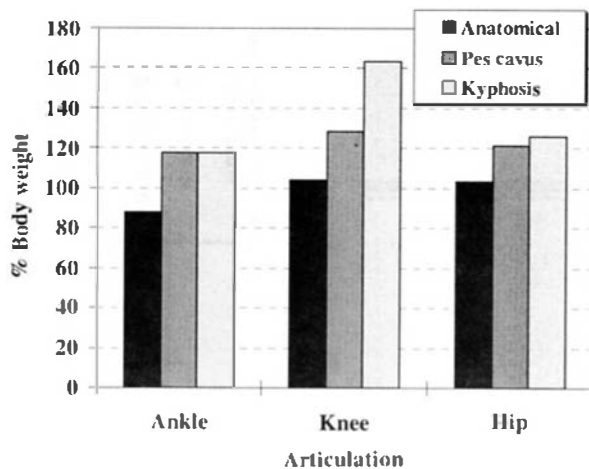


Fig. 7- Articular forces of lower extremity of body for different static postures.

EXAMPLE FOR BODY WITH GLOBAL SPINE KYPHOSIS

Global spine kyphosis affects the flexion of knees and hips [14]. We modeled this phenomenon with relative rotations of the lower extremity members in sagittal plane (Fig. 5c).

When the knees are flexed, contraction of the muscles which are inserted on patella (vastus) increases (Fig. 6). Increase of gluteus muscular forces is significant too. Relative rotation of legs due to the feet increases also the contraction force of soleus. The ground reaction force was moved toward the toes (Fig 5c, down).

DISCUSSIONS

We realized a new modeling method for lower extremity of body, with variable feet links. Using this model, we analyzed the muscular activities and articular forces, as well as the position vectors of the ground reaction forces, for some normal and pathological static postures. The results permit us to conclude:

1. The position of ground reaction forces, and consequently the position and length of feet segments, changes from heel to toes. Fixing the feet links on the ground could generate errors.
2. The muscular forces have important effects on articular forces. An example of body with pes cavus shows that increase of the contractile force of soleus increases the ankle articular force.
3. Even in static postures there are the muscular contraction. Naturally, body searches to find the best equilibrium. Not to considering this phenomenon could cause important errors.

4. The pathological postures could affect the muscular functions, and consequently the articular forces. This phenomenon could be observed in our example of body with global spine kyphosis. The osteotomy of spine kyphosis not only modifies the position of lower extremity members, but also changes the position of ground reaction forces. This clinical operation could decrease the muscular forces and permit us to reduce the energy necessary for body equilibrium.

Our model is very sensitive to the anatomical databases. In addition, the muscular forces were found for the maximum stimulations. In reality, the central nervous system controls the muscular contractions in some optimized way. Our model doesn't carry out this important need. It seems to us indispensable to joint this model to some other model, to control the muscular activities. It could be a neuro-muscular model or an optimization method, maybe for minimizing the ground reaction forces.

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