Investigation of Human Whole Body Motion Using a Three-Dimensional Neuromusculoskeletal Model

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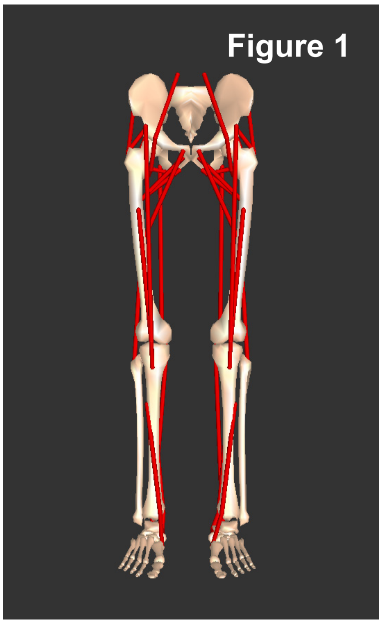
Abstract: We have been developing computer simulation models of the human body in order to simulate various forms of motions, e.g., walking, standing and jumping. In the earlier phase of our research, we utilized a simulation model of the human lower extremity that has nine rigid body segments. The number of degrees of freedom of the model was twenty. Using this model, two forms of jumping motions were simulated: a vertical jumping and a horizontal jumping. Behavior of muscles, tendons, joints and body segments were compared in detail between these two forms of jumping. In the latter phase of our research, we constructed another simulation model of the human whole body that has sixteen rigid body segments. The number of degrees of freedom of the model was thirty-five. Two major differences of this model from the previous one were: (1) the newly developed model has head, arms, hands, as well as three independent segments in the trunk, and (2) this model was developed so that the simulation program can be executed on any computers simultaneously. This modification enables us to simulate complex human whole body motions (such as throwing) fully utilizing the available computation power.

1. Computer simulation of maximal-effort vertical jumping

1.1. Introduction

Researchers often investigate various types of jumping motions in order to understand the mechanism of human body coordination during explosive activities. For that purpose, it is beneficial to quantitatively evaluate the action of each muscle throughout the motion. However, it is very difficult to perform this type of analysis using human subjects under experimental settings for technical and ethical reasons. Therefore, the procedure of computer modeling and simulation was utilized in this study. The purpose of this study was to simulate a human



maximal-effort vertical jumping motion with a sophisticated three-dimensional neuromusculoskeletal model. The specific aim was to evaluate the force, power and work outputs of lower limb muscles. Countermovement jumping motion was chosen, as this type of jumping is observed quite frequently in human daily / sports activities.

1.2. Methods

A neuromusculoskeletal model of the human body (trunk (including head and arms) and lower extremities) was developed using DADS-3D (LMS-CADSI) (Nagano et al., in press) (Figure 1). The skeletal model had nine rigid body segments connected with frictionless joints corresponding to the hip, knee, ankle, subtalar and metatarsophalangeal joints. The total number of degrees of freedom of the model was twenty. Models of thirty-two leg muscles (16 muscles in each leg) were implemented into the skeletal model. The neural activation input signal for individual muscles was represented by a series of step functions with a step duration of 50 ms. The excitation-contraction dynamics of the contractile element, the tissues around the joints that limit the joint range of motion (e.g., ligaments), as well as the foot-ground interaction were implemented (Nagano et al., 2005). A maximal-effort countermovement jumping was simulated from a static upright standing posture. The optimal pattern of the activation input signal was searched through random-search numerical optimization (Bremermann, 1970) with a goal of maximizing the jumping height (Figure 2).

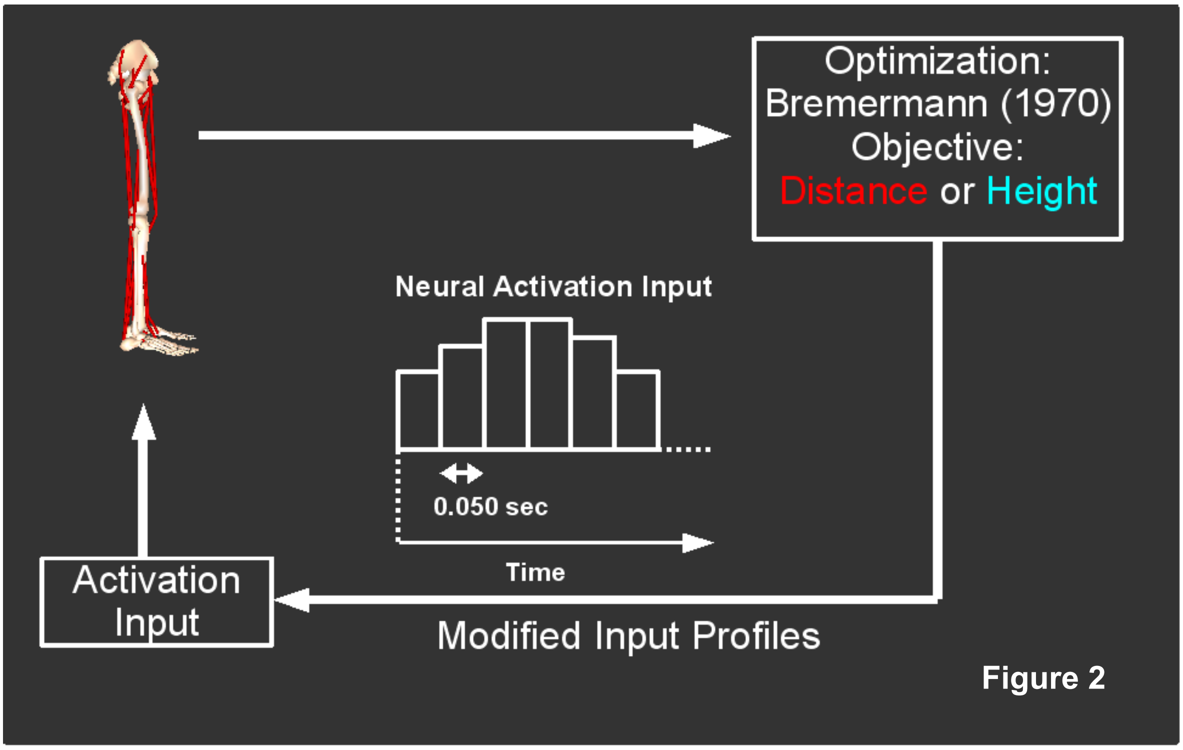
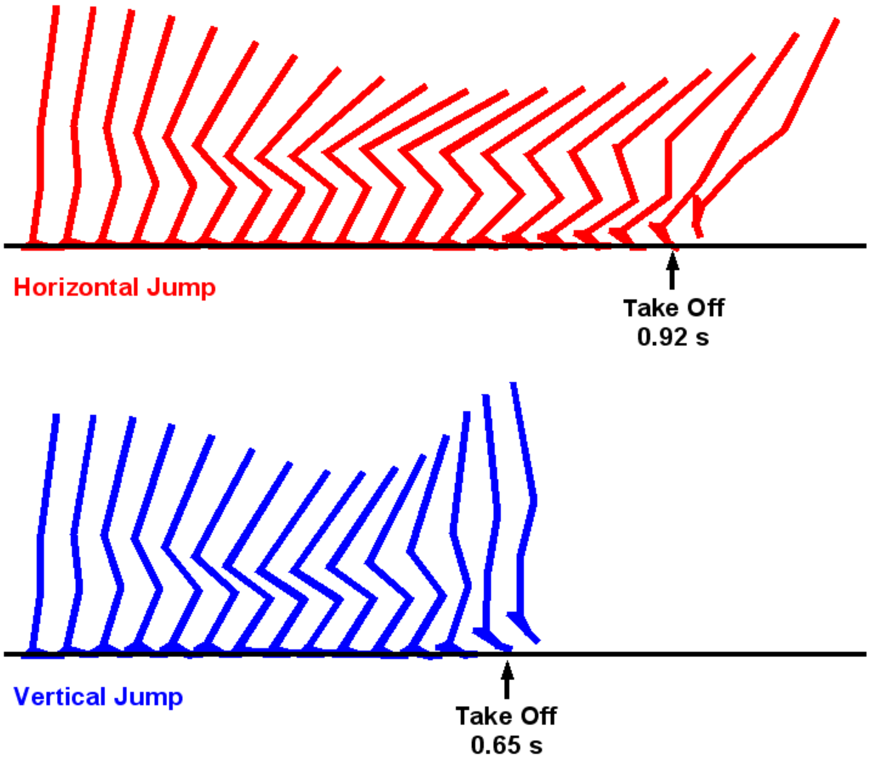


Figure 2

1.3. Results

The duration from the start of a motion (simulation) through the instant of take-off was 0.65 s (Figure 3). The maximal height reached by the mass center of body was 1.316 m above the floor. The amount of mechanical energy gain of the mass center of body throughout the jumping motion was 180.3 J. The total amount of work outputs from all muscles was 375.8 J. Realistic joint kinematics, ground reaction force profiles and muscle excitation patterns were generated.

Figure 3



1.4. Discussion

It was found that monoarticular muscles outputted large mechanical power and work, whereas biarticular muscles had only minor outputs in terms of mechanical power and work. Hip adductor, abductor and external rotator muscles were highly activated (~100%) during the jumping motion, although their power and work outputs were minor as these muscles did not undergo much shortening / lengthening. Muscles with a function of joint flexion such as mm. iliopsoas, m. biceps femoris short head and m. tibialis anterior were activated in the beginning of the downward phase, which had an effect of facilitating the generation of a countermovement.

(This part has been presented as: Nagano, A., Fukashiro, S., Himeno, R., 2004. Three-dimensional computer simulation of human maximal effort counter movement jump. Proceedings of: European Society of Biomechanics 2004 Conference (CD-ROM).)

2. Computer simulation of maximal-effort horizontal jumping

2.1. Introduction

As discussed previously, jumping motions have been studied by many researchers in the field of biomechanics. Many of those studies utilized various forms of vertical jumping as the subject. However, from the viewpoint of sports biomechanics, it is also important to investigate motion of the body in the horizontal direction. This is because it is often meaningful to maximize the horizontal distance of jumping during sports activities. Long jump in track and field is a good example. Even in other sports (such as basketball), typically athletes do not simply jump up vertically but generate a certain amount of horizontal momentum for the sake of achieving a good overall performance.

The purpose of this study was to examine the optimal coordination of a maximal-effort horizontal jumping. Mechanism of optimal control of horizontal jumping was compared with that of vertical jumping. For a fair comparison, two simulations (horizontal and vertical jump) were started from an identical initial condition, i.e., a static upright standing posture.

2.2. Methods

The model introduced previously was utilized for this study. Maximal-effort horizontal countermovement jumping motion was generated through forward dynamic computer simulation. A simulation was initiated from an upright posture with the hip, knee and ankle joints slightly flexed (5 degrees). Muscle activation input profiles were modified through random-search numerical optimization (Bremermann, 1970). Projectile motion of the mass center of body after jumping up was evaluated. The goal of the numerical optimization was to maximize the distance traveled by the mass center of body (Figure 2).

2.3. RESULTS

The duration from the start of a motion (simulation) through the instant of take-off was 0.92 s (Figure 3). The horizontal distance traveled by the mass center of body was 1.238 m, measured from the initial starting posture. The amount of mechanical energy gain of the mass center of body throughout the horizontal jumping was 258.9 J. The total amount of work outputs from all muscles was 357.3 J.

2.4. DISCUSSION

Mechanical energy gain of the mass center of body throughout the jumping motion was much greater in the horizontal jump (258.9 J) than in the vertical jump (180.3 J). This result is consistent with Nagano and Fukashiro (2000), in which the energy gain during a vertical jump was as much as 78% of the energy gain during a horizontal jump. As there was only a minor difference in the total muscle work output, it was implied that the muscular work was transferred to the mechanical energy of the mass center of body more effectively in the horizontal jumping.

A feasible explanation for this finding is in the difference of transfer of mechanical energy during the movements. In the horizontal jumping, the reduction of potential energy as the body segments were moved to a lower position was coupled with an increase of kinetic energy of those segments moving in the forward direction (Figure 2). Therefore there was a smaller loss of mechanical energy during the countermovement in the horizontal jumping. In the vertical jumping, the downward momentum generated during the countermovement had to be counteracted by muscular efforts before the body could start moving upward (Figure 2). Therefore there was a greater energy loss.

(This part has been presented as: Nagano, A., Komura, T., Himeno, R., Fukashiro, S., 2004. Human Maximal-effort horizontal and vertical jumping motions investigated using computer simulation. Proceedings of: The 5th Australasian Biomechanics Conference pp. 50-51.)

3. Development of a three-dimensional, whole-body simulation model of the human neuromusculoskeletal system

3.1. Introduction

It is widely recognized that computer simulation provides valuable contributions to the research of biomechanics. Using the methodology of forward dynamic computer simulation, it is possible to quantitatively evaluate influences of such biomechanical interventions as injury, surgical operations, strength training and so on.

Nonetheless, it is also true that this methodology has not been utilized handily by all researchers / research groups who are interested in using it. One of the reasons is that the procedure of modeling requires complex technical treatments. Although there are many commercial software packages to help this procedure (i.e., model development and simulation), even with the aid of these tools, this methodology is not being conveniently utilized by many researchers. This is not beneficial for the whole society, as high-impact contributions can be made by many researchers if this methodology becomes more accessible.

We thought that it would be meaningful to present a computer program of a human whole body model to the society of biomechanics. By simply copying the code, users can easily run a computer simulation of human whole body motions. The purpose of this study was to present a three-dimensional linked segment model of the human whole body skeletal system that has large degrees of freedom.

3.2. Methods

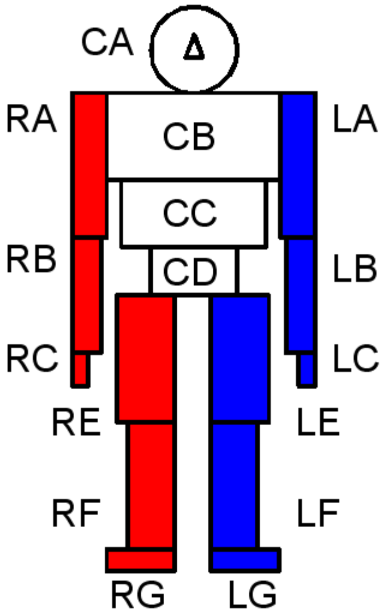


Figure 4

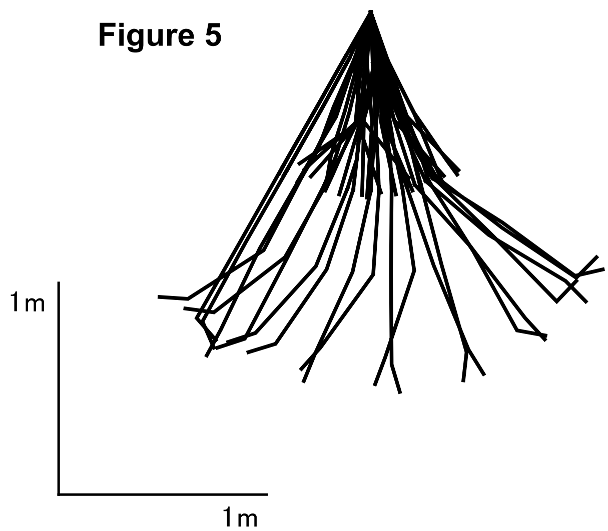
The model was coded to be processed with a modeling and simulation software package AUTOLEV (Kane and Levinson, 2004). The code will be posted on the internet for public access in the near future. The model has sixteen rigid body segments in total: head, chest, mid-trunk, lower-trunk, right and left upper arms, right and left lower arms, right and left hands, right and left upper legs, right and left lower legs, right and left feet (Figure 4). The number of degrees of freedom of the model was thirty-five. Anthropological parameter values (e.g., mass and moment of inertia of segments) were derived from De Leva (1996), Delp (1990) and Winter (1990).

As an example, a "hanging" motion was simulated using this model. The body was tilted in the forward direction by 30 deg. The upper endpoint of the head segment was fixed in the inertial coordinate system. Thereafter, a hanging motion was simulated in which the whole body swayed back and forth with an effect of the pull of gravity.

3.3. Results

It was shown that the code developed in this project can be utilized for a simulation of human whole body motion (Figure 5).

Figure 5



3.4. Discussion

In the future, the following four factors need to be taken into consideration to simulate a wider range of phenomena that researchers in biomechanics are interested in.

Those four major factors are: (1) muscles, (2) ground reaction forces, (3) detailed joint motions and (4) addition or removal of segments. Currently we are trying to address these points utilizing built-in functions of AUTOLEV, and making steady progresses.

(This part will be presented as: Nagano, A., Yoshioka, S., Komura, T., Himeno, R., Fukashiro, S. Development of a three-dimensional simulation model of the human whole body. 20th Congress of International Society of Biomechanics.)

4. References

Anderson, F.C., Pandy, M.G., 1999. A dynamic optimization solution for vertical jumping in three dimensions. Computer methods in biomechanics and biomechanical engineering 2, 201-231.

Bremermann, H., 1970. A method of unconstrained optimization. Mathematical Biosciences 9, 1-15.

De Leva, P., 1996. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. Journal of Biomechanics 29, 1223-1230.

Delp, S.L., 1990. Surgery simulation: a computer graphics system to analyze and design musculoskeletal reconstructions of the lower limb. Dissertation. Stanford University, Stanford, CA, USA.

Friederich, J.A., Brand, R.A., 1990. Muscle fiber architecture in the human lower limb. Journal of Biomechanics 23, 91-95.

Kane, T.R., Levinson, D.A., 2004. AUTOLEV 4 User's Manual. OnLine Dynamics, Inc., Sunnyvale, CA, USA.

Nagano, A., Fukashiro, S., 2000. Biomechanical comparison of the role of bi-articular rectus femoris in standing broad jump and vertical jump. Japanese Journal of Biomechanics in Sports and Exercise 4, 8-15.

Nagano, A., Umberger, B.R., Marzke, M.W., Gerritsen, K.G., 2005. Neuromusculoskeletal computer modeling and simulation of upright, straight-legged, bipedal locomotion of *Australopithecus afarensis* (A.L. 288-1). American Journal of Physical Anthropology 126, 2-13.

Nagano, A., Komura, T., Fukashiro, S., Himeno, R., in press. Force, work and power output of lower limb muscles during human maximal-effort countermovement jumping. Journal of Electromyography and Kinesiology.

Winter, D.A., 1990. Biomechanics and motor control of human movement. John Wiley & Sons, Inc., New York, NY, USA.