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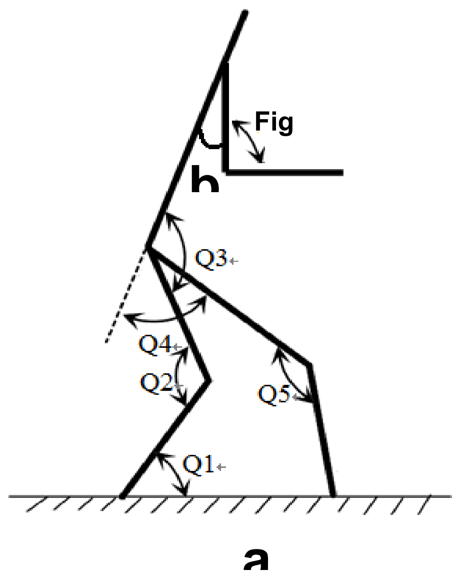
Whole-body fast reaching motions were simulated using a planar model with seven segments. Model movements were driven by joint torque generators and optimized for achieving the desired final posture within the shortest amount of time. Optimally simulated motion roughly matched the actual movement. It was found that the front hip joint activated first, followed by the rear hip joint, both lasting for only a short period. The rear knee joint extended to generate propulsion force in the middle and late phase of the motion. Contrary to common intuitions, the stretching arm motion was primarily driven by the rest of the body segments passively instead of activating actively. This might be explained by constraining motions (especially of the lower body) in two dimensions and fixating the rear arm on the trunk.

KEY WORDS: computer simulation, optimization, stepping, multi-body biomechanics.

INTRODUCTION: The reaching motion is a functional and practical movement that can often be seen in daily life. Moreover, to reach out for an object in the shortest time is a basic technique used in many kinds of sports activities, such as hitting/catching a ball, or in combat sports attacking the rival with hands or weapons. However, previous studies only focused on the upper body motions without considering whole body coordination and completion speed (Buneo, Soechting, & Flanders, 1994; Flanders, Pellegrini, & Soechting, 1994; d'Avella, Portone, Fernandez, & Lacquaniti, 2006). In addition, investigating the problem through experiments may be biased by subjects' past experiences and habits. Thus, generating whole-body fast reaching motions was explored with optimized computer simulations in this study.

Different from the pilot study with a 5-segment model containing only the trunk and lower body (Cheng & Kuo, 2011), a 7-segment model with the extra upper and lower arm on one side was used currently to study the optimal coordination strategy for whole-body fast reaching movements.

METHODS: The 7-segment model included the forearm and upper arm on the stretching side, trunk plus head with the other arm attached, and lower extremities with thighs and shanks on two sides (Figure 1). Rigid body segments are connected to each other with frictionless revolute joints. Although the rear leg is generally not in the same plane with the other body segments, to simplify the problem, motions are constrained to be in the sagittal plane. In addition, since obvious ankle dorsi/plantar flexion is usually not seen in this kind of movements, feet segments were not included. The equations of motion were generated by AUTOLEV. The model was driven by torque generators in each joint, and the torque of each joint can be calculated by multiplying the maximum isometric torque of $T_{max}(\theta)$ with a function $h(\omega)$ varying with joint angular velocity, and a function $A(t)$ representing the net activation of all the muscles exerting forces across a specific joint ($T = T_{max}(\theta)\ h(\omega)\ A(t)$).



Initial joint activation $A(t=0)$ can be calculated for maintaining a balanced initial static posture with body weight equally distributed on both ankles. It was supposed that each joint can keep its initial activation for a period of time t0, and subsequently start to activate for a time period t1 before deactivating. According to previous studies (Chiu, Cheng, Wang, Chen, & Wu, 2008; Selbie & Caldwell, 1996), the activation function $A(t)$ at any time instant can be calculated using the parameters t0 and t1. That is, with known joint angle and angular velocity, and the assumed t0 and t1 values, the specific joint torque profile can be determined. Since the front knee might extend and flex during the reaching motion, two torque generators were used to control its action. The other joints should merely extend, so only one torque generator was needed for each of them.

The rear ankle joint was assumed to be hinged on the ground without a torque generator. A spring was placed under the front ankle joint to generate the supporting ground reaction force. The desired final posture was achieved by constraining Q2, Q3, and Q7 = 180◦, Q5 = 90◦, the arm and front thigh being parallel to the ground, and the front ankle touching the ground at the end of movement simulation. The objective was to reach the desired final posture within the shortest amount of time. The optimization process started with randomly setting the control variables (t0 and t1 for each torque generator), and adjusting the control variables using the downhill simplex method to minimize the duration for completing the whole movement.

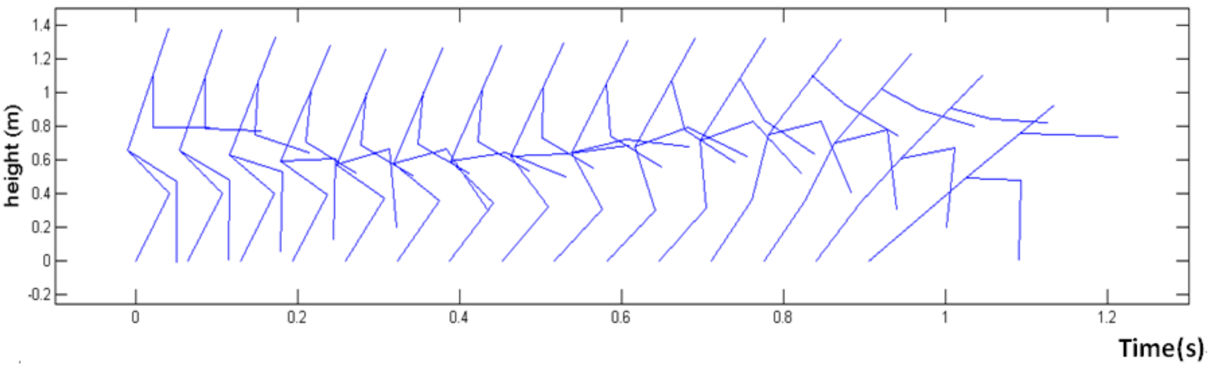


Figure 2: The optimally simulated motion. Positions of the rear ankle also represent the corresponding time instants.

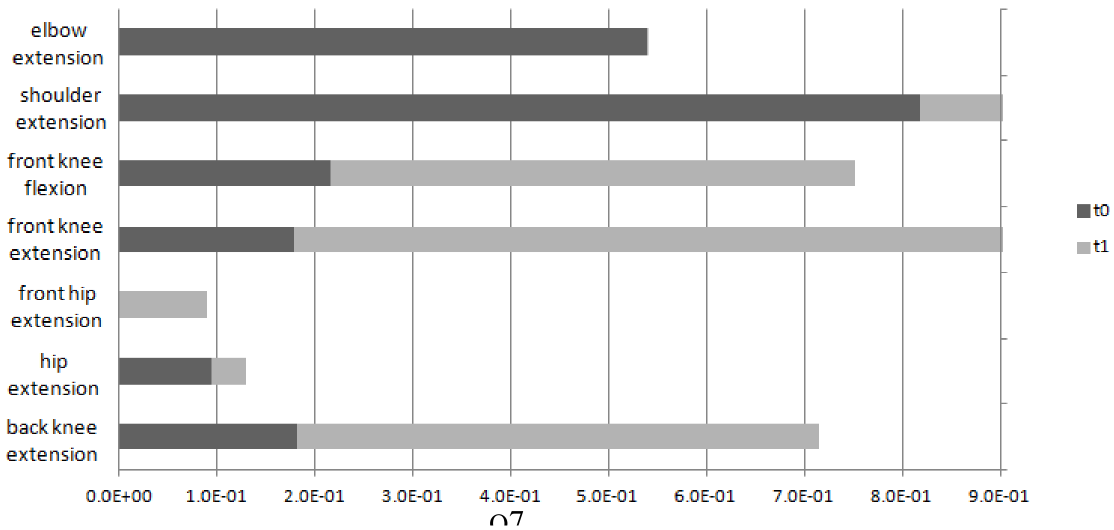


Figure 3: The sequence of joint activation

RESULTS: The optimally simulated motion is presented in Figure 2. The time for completing the reaching motion was about 0.9s, and the stride length was 1.127m. The front leg apparently lifted, extended, and flexed during the motion.

Figure 3 illustrates the sequence of joint activation. Blue bars represent the duration of maintaining initial activation, and red bars represent the duration between the onset of activation and deactivation. Front knee 1 and front knee 2 are for the extension and flexion of the front knee joint, respectively. The figure reveals that the front hip joint activated first, followed by the rear hip joint. Then the front knee extension and rear knee joint activated at almost the same time. Immediately after that was front knee flexion. Other the other hand, upper extremity joints maintained the initial activation to almost the end of the motion. In short, after lifting the front hip and extending the rear hip, the front and rear knees extended to bring the whole body forward, followed by front knee flexion in preparation for landing, and accompanied with arm extension to complete the desired posture.

DISCUSSION: The results revealed that the activation of both front and rear hips was short and only at the beginning of the motion to facilitate knee extension. The reaching motion was primarily driven by rear knee extension from the middle of the movement. The shoulder and elbow joints almost maintained the initial activation till the end, which means the upper extremities were driven by the rest of the body segments passively. This phenomenon is different from the intuition that the shoulder and elbow would extend actively, but also provides another aspect which shows that the extension of the arm may not rely entirely on the activation of the shoulder and elbow joints. Movements of the trunk and other segments may generate enough passive torque to allow the arms to reach forward.

Furthermore, compared with the pilot study (Cheng & Kuo, 2011), the initial COG position in this study seemed higher. The COG position lowered a little at the beginning and then rose with the lifting front leg, and lowered again to land, thus costing more time to accomplish the desired posture. Once the COG escalated, the horizontal component of propulsion force form rear ankle would decrease and the vertical component would increase, which could lower the efficiency of propulsion force and increase the duration of the reaching motion.

CONCLUSION: An optimally simulated whole-body fast reaching motion was presented in this study. It was found that hip joints only activated a short time, the rear knee joint extended to generate the propulsion force in the middle and late phases of the motion. The shoulder and elbow joints merely maintained the initial activation during the entire motion. Contrary to common intuitions, the stretching arm motion was primarily driven by the rest of the body segments passively instead of activating actively. This might be explained by constraining motions (especially of the lower body) in two dimensions and fixating the rear arm on the trunk.

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