Planar Vertical Jumping Simulation-A Pilot Study

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Abstract. Vertical jumping is one of the fundamental motions among other jumping types in sport biomechanics. Two important criteria in sport biomechanics are critical to all athletes: Injury and performance. In literature two major approaches have been investigated: experiment-based methods and optimization-based methods. Experiment-based methods are time consuming and tedious. Optimization-based methods for musculoskeletal models are computationally expensive because their models include all muscles and explicit integration of equation of motion. In this pilot study, a direct optimization-based method for a skeletal model was proposed in sagittal plane, where this formulation was based on joint space that was only considered the resultant results of muscles (joint torques) instead of individual muscles to reduce computational time. The cost function included increasing the center of mass velocity at take-off and increasing the center of mass position at take-off. Constraints included joint limits, torque limits, initial posture, ground contact, initial angular velocity and acceleration, zero-ground reaction forces, and moment at take-off. This optimization problem was solved by a commercial optimization solver SNOPT and the CPU time was 227 seconds on a regular PC (Intel® Core® 2 duo CPU, 3.16 GHZ and 3.25 GB RAM). Preliminary results highly correlated results from the literature. This simple planar simulation is the first step to understand the cause and effect for vertical jumping with or without arm swing.

Keywords: Vertical jumping; planar model; injury; performance, arm swing.

1 Introduction

Jumping is a fundamental human movement and a vital skill, especially in sports, that requires a coordination of lower and upper extremities. This movement consists of three stages: propulsive stage, flying stage and finally landing stage. Because of the contact of the foot with the ground at the end of propulsive stage, it is prone to injuries. In order to prevent the injuries and also find out how to increase the performance, significant research has been done to this area. A literature review (Ozsoy et. al, 2010) about vertical jumping was performed.

In literature two major approaches have been investigated: experiment-based methods and optimization-based methods. Experiment-based methods are time consuming and tedious, also it can give investigate the problem only for the subject's

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performance. Optimization-based methods can predict the motion but they are computationally expensive because their models include all muscles.

There are many studies about the investigation of different types of jumps such as squat vertical jumping and countermovement jumping with and without arm swing (Luthanen et al., 1978, Shetty et al., 1989, Khalid et al., 1989, Harman et al., 1990, Lees et al., 2004, Hara et al, 2006, Pandy et al., 1990, Cheng et al., 2008).

In this study, optimization-based recursive dynamic formulation was proposed for the planar simulation for jumping in sagittal plane where this formulation was based on joint space that was only considered the resultant results of muscles (joint torques) instead of individual muscles to reduce computational time. The problem formulation was subjected to a set of constraints. Cost function which was the maximization of the performance of jump included two terms: vertical center of mass position at take-off and vertical center of mass velocity at take-off. The current problem formulation can investigate the cause and effect easily therefore it was also used for investigating the effect of arm swing to the performance of jump.

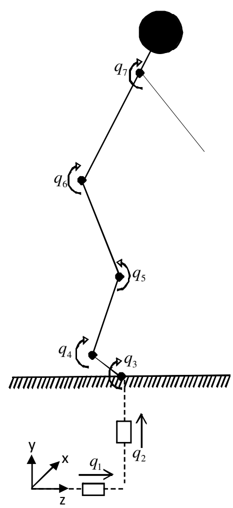


Fig. 1. Planar body model

2 Human Body Model

In this study, a planar body model with 7 degrees of freedom was developed. The body model consisted of foot, shank, thigh, trunk, and arm. The body in sagittal plane model was shown in Figure 1. One revolute DOF for shoulder, hip, knee, and ankle was defined, respectively, three global DOFs (2 prismatic and one revolute) were defined, and the global coordinate system was fixed on the ground. The joint angle vector was defined as $\mathbf{q} = [q_1 \quad q_2 \quad \ldots \quad q_7]^T$. The revolute joints used in the body model were modeled as frictionless hinge joint. The three global DOFs were considered as virtual joints which were used for calculation of GRFs. The body model parameters, link lengths, link masses, moments of inertia and center of masses were taken from a previous study (Cheng et al., 2008).

The human body can be modeled as a kinematic chain consisting of revolute joints representing the musculoskeletal joints and are connected by links that represent the bones. A local Cartesian coordinate system was fixed to each link and simulated motion was created by rotating each of the joints about this local z-axis. The model was represented by generalized coordinates (q_i). Since the generalized coordinates were measured about the local axis, transformation matrices were needed for each joint and generated with Denavit-Hartenberg (DH) method (Denavit and Hartenberg, 1955).

3 Dynamics Model

In this study, the problem of the motion prediction of a two-dimensional human body model was formulated as an optimization problem. The recursive Lagrangian dynamics which includes forward recursive kinematics and backward recursive dynamics was used.

3.1 Forward Recursive Kinematics

Transformation matrices obtained from the DH-method can be used to determine the forward kinematics. The procedure was shown below.

$$\mathbf{A}_j = \mathbf{T}_1\mathbf{T}_2\mathbf{T}_3 ...\mathbf{T}_j = \mathbf{A}_{j-1}\mathbf{T}_\mathrm{j} \tag{1}$$

$$\mathbf{B}_j = \dot{\mathbf{A}}_j = \mathbf{B}_{j\text{-}1}\mathbf{T}_j + \mathbf{A}_{j\text{-}1}\frac{\partial \mathbf{T}_j}{\partial q_j}\dot{q}_j \tag{2}$$

$$\mathbf{C}_j = \dot{\mathbf{B}}_j = \ddot{\mathbf{A}}_j = \mathbf{C}_{j-1}\mathbf{T}_j + 2\mathbf{B}_{j-1}\frac{\partial \mathbf{T}_j}{\partial q_j}\dot{q}_j + \mathbf{A}_{j-1}\frac{\partial^2 \mathbf{T}_j}{\partial^2 q_j}\dot{q}_j^2 + \mathbf{A}_{j-1}\frac{\partial \mathbf{T}_j}{\partial q_j}\ddot{q}_j \tag{3}$$

where $\mathbf{A}_0$ = 1 (identity matrix) and $\mathbf{B}_0 = \mathbf{C}_0 = \mathbf{0}$. After the calculation of transformation matrices, the global position, velocity and acceleration of a point in Cartesian space can be calculated as:

$${}^0\mathbf{r}_j = \mathbf{A}_j\mathbf{r}_j\,,\ {}^0\dot{\mathbf{r}}_j = \mathbf{B}_j\mathbf{r}_j\,,\ {}^0\ddot{\mathbf{r}}_j = \mathbf{C}_j\mathbf{r}_j \tag{4}$$

3.2 Backward Recursive Dynamics

Torques at each joint that generate the motion were calculated with given mass inertia properties of each link, I_i, external force $\mathbf{f}_k^\mathrm{T} = [{}^kf_x \quad {}^kf_y \quad {}^kf_z \quad 0]$ and the external moment $\mathbf{h}_k^\mathrm{T} = [{}^kh_x \quad {}^kh_y \quad {}^kh_z \quad 0]$ for the link k defined in global coordinate system. The equation consists of four components: torque due to inertia and coriolis acceleration, gravity, external forces, and external moments.

$$\tau_i = \mathrm{tr}[\frac{\partial \mathbf{A}_i}{\partial q_i}\mathbf{D}_i] + \mathbf{g}^{\mathrm{T}}\frac{\partial \mathbf{A}_i}{\partial q_i}\mathbf{E}_i + \sum_{k=1}^{\mathrm{n}}\mathbf{f}_k^{\mathrm{T}}\frac{\partial \mathbf{A}_i}{\partial q_i}\mathbf{F}_i^k + \sum_{k=1}^{\mathrm{n}}(\mathbf{G}_i^k)\mathbf{A}_{i\text{-}1}\mathbf{z}_0 \tag{5}$$

where

$$\mathbf{D}_i = \mathbf{I}_i\mathbf{C}_i^{\mathrm{T}} \tag{6}$$

$$\mathbf{E}_i = m_i\,{}^i\mathbf{r}_{\mathrm{i}} + \mathbf{T}_{i+1}\mathbf{E}_{i+1} \tag{7}$$

$$\mathbf{F}_i^k = {}^k\mathbf{r}_f\delta_{ik} + \mathbf{T}_{i+1}\mathbf{F}_{i+1} \tag{8}$$

$$\mathbf{G}_i^k = \mathbf{h}_k\delta_{ik} + \mathbf{G}_{i+1} \tag{9}$$

$\mathbf{D}_{n+1} = \mathbf{0}$ and $\mathbf{E}_{n+1} = \mathbf{F}_{n+1} = \mathbf{G}_{n+1} = \mathbf{0}$; $\mathbf{I}_i$ was the inertia matrix for link i; m_i was the mass of link i; $\mathbf{g}^T = \begin{bmatrix}0 & -g & 0 & 0\end{bmatrix}$ was the gravity vector; ${}^i\mathbf{r}_i$ was the location of center of mass of link i in the local frame i; ${}^k\mathbf{r}_f$ was position of the external force in the local frame k; $\mathbf{z}_0 = \begin{bmatrix}0 & 0 & 1 & 0\end{bmatrix}^{\mathrm{T}}$ for a revolute joint and $\mathbf{z}_0 = \begin{bmatrix}0 & 0 & 0 & 0\end{bmatrix}^{\mathrm{T}}$ for a prismatic joint. δ_{ik} is Kronecker delta.

4 Numerical Discretization

The motion has to be discretized for numerical calculation. The entire time domain was discretized by 3rd order B-spline curves due to the important properties of local control, differentiability and continuity. As the motion was generated by the joint torques, motion plans for each joint angular position, velocity and acceleration were predicted by 3rd order B-spline which is a function of control points, and basis function. When the joint angular position as a function of time was predicted, its first and second derivatives were the profiles for angular velocity and acceleration.

5 Optimization Formulation

In this section, the problem formulation developed in this study was described. The design variables, objective function and the constraints used in the simulation were explained.

5.1 Design Variables

In the optimization formulation, the design variables were the control points in B-spline curves. As the total time of the motion and number of steps are given into the problem formulation, the knots were already defined as an input. Therefore the optimization problem took part in order to predict the control points to generate the motion planning for jumping with given objective function.

5.2 Objective Function

The jumping motion which requires a coordination of the upper and lower extremities can be considered as two-dimensional projectile motion. The objective function was to maximize the center of mass position at the apex of the flight. Center of mass position (X_{CM}) at the apex of the flight depends on two variables: Center of mass position and velocity (V_{CM}) at take-off. Therefore the problem was considered as multi-objective optimization (MOO) problem. The objective function was given in (10) where w_1 and w_2 were the weight values and considered as 1.

$$\max\left(w_1 X_{CM@Take\text{-}off} + w_2 \frac{V^2_{CM@Take\text{-}off}}{2g} \right) \tag{10}$$

Center of mass position can be calculated directly from the orientation of the individual segments; however, the center of mass velocity required additional calculation. In order to calculate the center of mass velocity, impulse-momentum relationship can be used (Harman et al., 1990). The relationship was shown in (11) where m_t was the total mass of the body, W was the weight of body and GRF_y was vertical ground reaction force and t_o was the time at take-off where the optimization was ended.

$$V_{CM@take\text{-}off} = \frac{1}{m_t}\int_0^{t_o} GRF_y \text{ - } W dt \tag{11}$$

5.3 Constraints

In order to predict the realistic human vertical jump, several constraints were implemented to the problem. These constraints are: Joint limits, torque limits, initial posture, ground contact, initial angular velocity and acceleration, zero-GRFs and moment at take-off.

Joint Angle Limits. Joint angle limits were constrained to prevent the hyper-extension and to predict the motion in physical range. The angular position for each joint should remain between the upper and lower physical limits as shown in (12).

$$q_i^L \le q_i(t) \le q_i^U \qquad 0 \le t \le t_o \tag{12}$$

In restricted arm-swing jump simulation, the arm movement was prevented by setting the joint limit of arm to a value as a function of time where the arms are parallel to the trunk.

Joint Torque Limits. In this study, the problem formulation was based on joint space that was only considered the resultant results of muscles (joint torques) instead of individual muscles to reduce computational time. Also as well as the joint angle limits, the joint torques were constrained as shown in (13) to define the problem in physical range. The joint torque limits were taken from the literature.

$$\tau_i^L \le \tau_i(t) \le \tau_i^U \qquad 0 \le t \le t_o \tag{13}$$

Initial Posture. The initial posture for the simulation was obtained through experiments. The performance of the jumping also depends on the initial posture. A posture reconstruction algorithm was applied to the experimental data to determine the initial joint angle positions where the body were in static equilibrium.

Ground Contact. As only the first stage of the jumping was predicted in this study, there was always contact between the body and the ground. The origin was placed to the toe and the position of it was constrained in horizontal and vertical direction.

Initial Angular Velocity and Acceleration. When the body was in static equilibrium at the beginning of the movement, the vertical GRF should be equal to the body weight. Therefore all the initial angular joint velocities and accelerations are constrained to zero for this purpose.

Zero Ground Reaction Force and Moment at Take-Off. In order to finalize the prediction of motion, zero GRFs and GRM constraints were used. The physical meaning of this constraint is releasing the ground contact constraint where the motion starts the second stage which is flying.

6 Results and Discussion

The kinematic results of the simulations with arm swing (5S) and without arm swing (4S) are shown in Table 1.

Table 1. Results of jumping with and without arm swing

Kinematic results	4S	5S
Time elapsed before take-off [s]	0.43	0.5
CM position at take-off [m]	0.899	0.939
CM vertical velocity at take-off [m/s]	2.315	2.676
Maximum CM height at apex [m]	1.172	1.304

Total time of the jumping required was used as an input which was obtained from the experiment for both types of jumps. It can be obviously seen that the jumping with arm swing required more time which increased the center of mass position and velocity at take-off at take-off. The center of mass position and velocity profiles were shown as a function of time in Figure 2 and 3. As it can be seen from Figure 2, vertical center of mass positions at the beginning were not same for 4S and 5S jumps due to different orientation of arm segment.

In order to predict a realistic jumping, the body remained in a static posture at the beginning of the motion and then relaxed as shown in Figure 4 and 5 for both types of jumping. This relaxation period yielded a negative vertical velocity at the beginning for 5S jump. For 4S jump vertical CM velocity became slightly less than zero at 0.2 s before take-off. The reason of different timings of becoming negative velocity may be due to arm swing. The maximum vertical center of mass velocity achieved for 5S

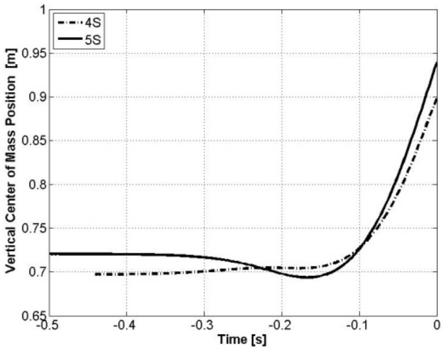


Fig. 2. Vertical CM position profile

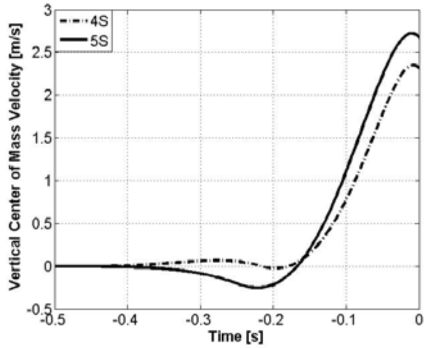


Fig. 3. Vertical CM velocity profile

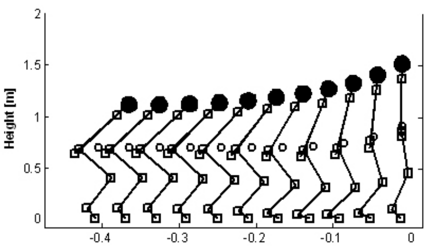


Fig. 4. Stick diagram postures without arm-swing as a function of time

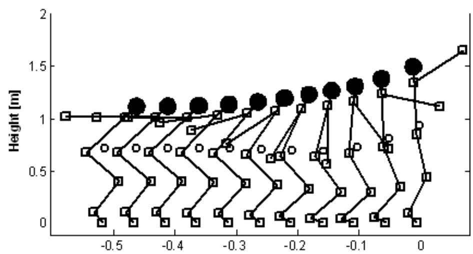


Fig. 5. Stick diagram postures with arm-swing as a function of time

jump was predicted 2.724 m/s at 0.010s before take-off where for 4S jump it was 2.349 m/s at 0.011s before take-off. The increase of the CM position from beginning to take-off is predicted as 0.260 m with arm swing and 0.181 m without arm swing. The CM velocity at take-off was found as 2.676 m/s and 2.314 m/s with and without arm swing respectively. This results are close to the values found as 2.71m/s and 2.51 m/s (Hara et al., 2006), 2.81 m/s and 2.58 m/s (Feltner et al., 1999) .

Vertical GRFs for both 4S and 5S started with a value equal to the body weight due to the constraint of zero angular velocity and acceleration at the beginning. Due to the relaxation period at the beginning, there were decreases in vertical ground reaction profiles and then they started to increase.

The arm swing lengthened pre-take-off duration and yielded a higher peak value at the latter half of the jumping as shown in Figure 6. Take-off velocity, which was calculated by impulse-momentum relationship, was enhanced by 0.361 m/s with contribution of arm swing. The contribution of the velocity to the performance was found by 69.1%, where the remaining 30.9% was due to the higher center of mass position at take-off.

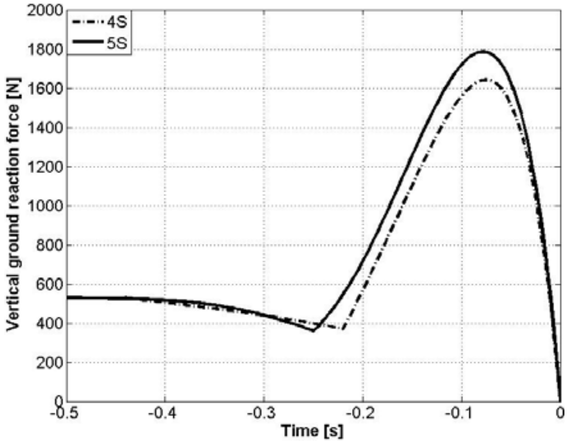
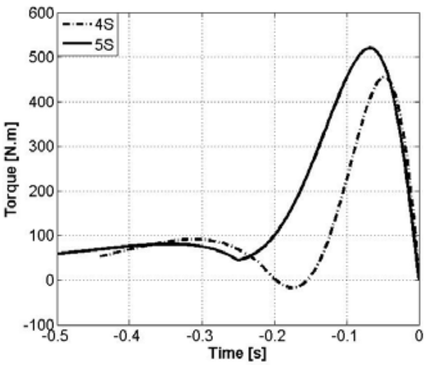
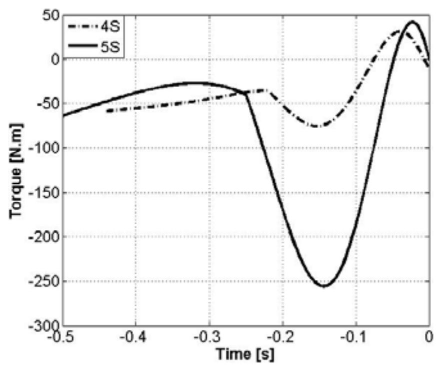


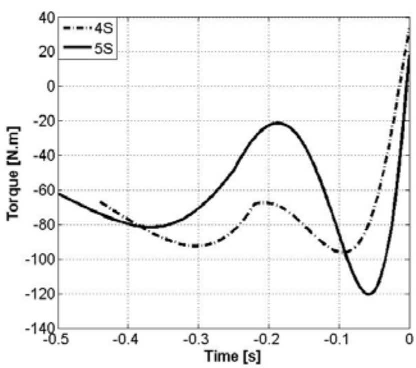
Fig. 6. Vertical GRF profiles



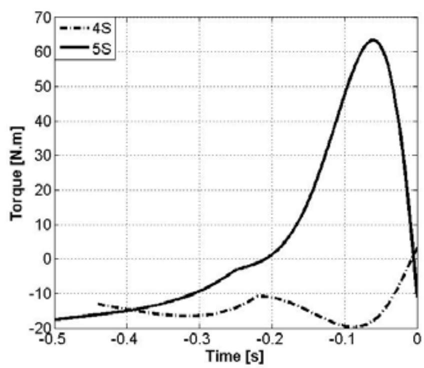
(a) Ankle joint torque profiles



(b) Knee joint torque profiles



(c) Hip joint torque profiles



(d) Shoulder joint torque profiles

Fig. 7. Joint torque profiles

At the former half of the both 4S and 5S jump, the torque profiles showed same trend for 4S and 5S as shown in Figure 7. The effect of arm swing to lower extremities was too obvious especially for the knee and hip joint.

A the latter half of the jump, they achieved higher torques due to arm swing.

7 Conclusion

This paper presented a computationally efficient direct optimization-based motion prediction method for planar vertical jumps with and without arm swing. Resultant joint torques were used in calculations instead of muscles to reduce computational time. Simulations took 227 seconds with a regular PC (Intel® Core® 2 duo CPU, 3.16 GHz and 3.25 GB RAM). According to the simulation results, vertical center of mass take-off velocities were found 2.676 m/s and 2.315 m/s where the vertical center of mass positions were 0.939 m and 0.899 m for jumping with arm swing and without arm swing respectively. The performance increase which is the position of the center of mass can reach at flying stage was 69.1 % due to enhanced velocity and the remaining 30.9% was due to higher center of mass position. Take-off velocity was calculated with impulse-momentum relationship which means the enhanced take-off velocity was due to higher vertical ground reaction profile and more contact time duration.

In conclusion, this simple model is useful to understand the vertical jumping and investigate the cause and effect easily. Preliminary results were obtained through this new formulation and matched the literature results.

Future work includes 1) embedding time as a design variable that can be used to optimize time for vertical jumping; 2) extending the planar example to a 3 dimensional (3D) human model with high degrees of freedom; 3) validation of the simulation results for 3D model; 4) including landing in the optimization to study the landing strategies to reduce injuries.

References

1. Cheng, K.B., Wang, C.H., Chen, H.C., Wu, C.D., Chiu, H.T.: The mechanisms that enablearm motion to enhance vertical jump performance-A simulation study. Journal of Biomechanics 41, 1847–1854 (2008)
2. Denavit, J., Hartenberg, R.S.: A kinematic notation for lower-pair mechanisms based on matrices. Journal of Applied Mechancis 22, 215–221 (1955)
3. Feltner, M.E., Frasceti, D.J., Crisp, R.J.: Upper extremity augmentation of lower extremity kinetics during countermovement vertical jumps. Journal of Sports Sciences 17, 449–466 (1999)
4. Hara, M., Shibayama, A., Takeshita, D., Fukashiro, S.: The effect of arm swing on lower extremities in vertical jumping. Journal of Biomechanics 39, 2503–2511 (2006)
5. Harman, E.A., Rosenstein, M.T., Frykman, P.N., Rosenstein, R.M.: The effects of arms and countermovement on vertical jumping. Medicine and Science in Sports and Exercise 22, 825–833 (1990)
6. Khalid, W., Amin, M., Bober, T.: The influence of upper extremities movement on take-off in vertical jump. Biomechanics in Sports, 375–379 (1989)

7. Lees, A., Vanrenterghem, J., Clercq, D.D.: Understanding how an arm swing enhances performance in the vertical jump. Journal of Biomechanics 37, 1929–1940 (2004)
8. Luhtanen, P., Komi, P.V.: Segmental contribution to forces in vertical jump. European Journal of Applied Physiology and Occupational Physiology 38, 181–188 (1978)
9. Ozsoy, B., Yang, J., Boros, R.: Human jumping motion analysis and simulation- a literature review. In: 3rd International Conference on Applied Human Factors and Ergonomics, Miami, Florida, July 17-20 (2010)
10. Pandy, M.G., Zajac, F.E., Sim, E., Levine, W.S.: An optimal control model for maximum-height human jumping. Journal of Biomechanics 23, 1185–1198 (1990)
11. Shetty, A.B., Etnyre, B.R.: Contribution of arm movement to the force components of a maximum vertical jump. Journal of Orthopedic and Sports Therapy 11, 198–201 (1989)