Estimation of anthropometrical and inertial body parameters

J. Bastien*, Y. Blache* and K. Monteil*

** EA 647, Centre de Recherche et d'Innovation sur le Sport, Université Claude Bernard-Lyon 1, 27-29, Bd du 11 Novembre 1918, 69622 Villeurbanne Cedex, France; jerome.bastien@univ-lyon1.fr; yoann.blache@univ-lyon1.fr; karine.monteil@univ-lyon1.fr*

Abstract. The inertial (IP) and anthropometrical (AP) parameters of human body are mostly estimated from coefficients issue from cadaver measurements. These parameters could involve errors in the calculation of joint torques during explosive movements. The purpose of this study was to optimize the IP and AP in order to minimize the residual torque and force during squat jumping. Three methods of determination have been presented: method A: optimizing AP and IP of each body part; method B: optimizing trunk AP and IP, assuming that the AP and IP of the lower limbs were known; method C: using Winter AP and IP. For each method, the value (degree 0), the integral (degree 1) and the double integral (degree 2) of the residual moment were also used. The method B with degree 2 was the most accurate to determine trunk AP and IP by minimizing the residual force and torque, by providing a linear least squares system. Instead of minimizing the residual force and torque, by classical way, the double integral of the latter provided more accurate results.

1. Introduction

Joint forces and torques are commonly used in motion analysis for orthopedics, ergonomics or sports science [1, 2]. A standard bottom-up inverse dynamic model is often used to calculate joint forces and torques at the lower extremity. Body anthropometric (AP) and inertial parameters (IP) are needed to apply inverse dynamic model. AP and IP can be obtained from many ways. Cadaver measurements have been the first method applied by researchers and is still commonly used [3–7]. Then, predictive linear or non-linear equation [8–12] and imaging resonance magnetic techniques [13–17] have been elaborated. In Hatze study [18], the author has been interested in the accuracy of the different methods. He observed that the methods using γ ray, X ray, tomography and imaging resonance magnetic techniques presented an average accuracy of 5% with a maximal error of 11%. Linear regression yields AP and IP with an average accuracy of about 24% with a maximal error of 40%. The corresponding values for non-linear regression were 16% and 38% respectively. According to Hatze [18], the most accurate technique would be the anthropometrico-computational method with 1.8% of average accuracy and 3% of maximal error.

Some authors tried to evaluate the influence of error in AP and IP on joint torques during gait analyses. In [19], the authors compared joint torques during walking using cadaver AP and IP [7] versus direct measurements [20]. In [21], 6 methods to calculate AP and IP were compared. Even if these methods provided different AP and IP, no effect on torque measurements were pointed out during walking. Nevertheless, in [21], the authors concluded that changes in AP and IP should have a greater influence on the torque measurements for activities involving greater accelerations. This is the case in squat jumping, where the push-off lasts around 350 ms, and the acceleration of the body center mass could reach 20 $m.s^{-2}$. Researchers mainly use cadaver measurements [22–27] or predictive equations [28–34] during studies about vertical jumping. However these methods give AP and IP which are not specific to the population studied. As a result, some errors in AP and IP could imply inaccuracy in joint torque calculations.

Besides, to the best of our knowledge, no study has focused on the optimization of AP and IP in explosive movements and especially in 2-D squat jumping investigation. Therefore the purpose of this study was to adjust AP and IP of the human segments during squat jumping in order to minimize error in joint torque values. Especially, the optimization will focus on the "head arm trunk" segment (HAT).

2. Methods

2.1 Experimental acquisition

Twelve healthy athletic male adults (mean ± SD: age, 23.2 ± 3.6 years; height, 1.75 ± 0.06 m; mass, 69.1 ± 8.2 kg) volunteered to participate in the study and provided informed consent. Prior to the experimental protocol, reflective landmarks were located on the right 5-th metatarsophalangeal, lateral malleolus, lateral femoral epicondyle, greater trochanter and acromion. Thereafter, the subjects performed at most ten maximal squat jumps. In order to avoid the contribution of the arms in vertical jump height [29, 31], the subjects were instructed to keep their hands on their hip throughout the jump.

All jumps were performed on an AMTI force plate model OR6-7-2000 sampled at 1000 Hz. Countermovement defined as a decrease of vertical ground reaction force (R_y) before the push-off phase was not allowed.

The beginning of the push-off was considered as the instant when the derivative of the smoothed R_y is different to zero. Simultaneously, the subjects were filmed in the sagittal plane with a 100 Hz camcorder (Ueye, IDS UI-2220SE-M-GL). The optical axis of the camcorder was perpendicular to the plane of the motion and located at 4 meters from the subject.

Jumps recorded were digitalized frame by frame with the Loco® software (Paris, France). A four rigid segments model composed of the foot (left and right feet together), the shank (left and right shanks together), the thigh (left and right thighs together) and the HAT (head, arms and trunk) was used. Squat jump being a symmetrical motion, the lower limb segments were laterally combined together and it was supposed that the left and right sides participate equivalently to the inter- articular efforts. The position of the upper limbs is fixed to limit their influence on I_4. Moreover the objective is to provide a robust estimate of the I_4 according to a given protocol and to observe that it is different from that of Winter.

Data obtained from the video and the force platform were synchronized and then smoothed in order to be derivated one or twice.

2.2 Calculation of residual error

The dynamics equations applied to each of the segments [AjAj+1], for j ∈ {1, …, q-1}, give

$$\overrightarrow{R_j} - \overrightarrow{R_{j+1}} = -m_j\vec{g} + m_j \frac{d^2\overrightarrow{OG_j}}{dt^2} \tag{1a}$$

$$-M_j + I_j\ddot{\theta}_j = C_j - C_{j+1} \tag{1b}$$

where

$$M_j = -(x_{j+1} - x_j)(\alpha_j R_{y,j} + (1-\alpha_j)R_{y,j+1}) + (y_{j+1} - y_j)(\alpha_j R_{x,j} + (1-\alpha_j)R_{x,j+1}) \tag{2}$$

With boundary condition

$$\overrightarrow{R_1} = \vec{R}\ ,\ \ \vec{R}_p = \vec{0} \tag{3}$$

$$C_1 = C\ ,\ \ C_q = 0 \tag{4}$$

We obtain classically for all k ∈ {1, …, q-1},

$$\vec{R}_k = \vec{R} - \sum_{j=1}^{k-1} m_j \left(\frac{d^2\overrightarrow{OG_j}}{dt^2} - \vec{g} \right) \tag{5a}$$

$$C_k = C + \sum_{j=1}^{k-1} \left(M_j - I_j \ddot{\theta}_j \right) \tag{5b}$$

and

$$C = -\sum_{j=1}^{q-1} M_j - \sum_{j=1}^{q-1} I_j \ddot{\theta}_j \tag{5c}$$

The residual torque is defined by

$$\tilde{C} = C + \sum_{j=1}^{q-1} M_j - \sum_{j=1}^{q-1} I_j \ddot{\theta}_j \tag{6}$$

Where angles θ_j are determined from the smoothed displacements, M_j are defined by (2) and joint forces $R_{x,j}$ and $R_{y,j}$ are calculated by using (5a).

We now explain how to determine I1, I2, I3 and I4. The residual torque is defined by (6) or by the following equation:

$$\tilde{C}^{(0)}(t) = C_{exp} - C_{angl} \tag{7a}$$

Where C_{exp} is torque measured experimentally and

$$C_{angl} = -\sum_{j=1}^{q-1} M_j + \sum_{j=1}^{q-1} I_j \ddot{\theta}_j \tag{7b}$$

is defined according to moments M_j and the double derivatives $\ddot{\theta}_j$. $X^{(0)}$ corresponds to the values of function X.

The impulsion phase is equal to $[t_0, t_f]$.

By integration, between the beginning t_0 and t_i, and since the angular velocities are null at onset of push-off, we obtain

$$\tilde{C}^{(1)}(t_i) = C_{exp}^{(1)}(t_i) - C_{angl}^{(1)}(t_i) \quad (8a)$$

$$C_{exp}^{(1)}(t_i) = \int_{t_0}^{t_i} C_{exp}(s)ds \quad (8b)$$

$$C_{angl}^{(1)}(t_i) = -\sum_{j=1}^{q-1} \int_{t_0}^{t_i} M_j(s)ds + \sum_{j=1}^{q-1} I_j \dot{\theta}_j(t_i) \quad (8c)$$

Where *s* is the variable of integration. $X^{(1)}$ corresponds to the first order integration of the function *X*. After a second integration we obtain:

$$\tilde{C}^{(2)}(t_i) = C_{exp}^{(2)}(t_i) - C_{angl}^{(2)}(t_i) \quad (9a)$$

$$C_{exp}^{(2)}(t_i) = \int_{t_0}^{t_i} \int_{t_0}^{u} C_{exp}(s)ds\, du \quad (9b)$$

$$C_{angl}^{(2)}(t_i) = -\sum_{j=1}^{q-1} \int_{t_0}^{t_i} \int_{0}^{u} M_j\,(s)dsdu + \sum_{j=1}^{q-1} I_j \left(\theta_j(t_i) - \theta_j(t_0)\right) \quad (9c)$$

Where *u* is the second variable of integration. $X^{(2)}$ corresponds to the second order integration of the function *X*. In order to compare the residual values $\tilde{C}^{(0)}$, $\tilde{C}^{(1)}$ and $\tilde{C}^{(2)}$ obtained with different methods, it is necessary to normalize these values by considering the dimensionless quantity defined by

$$\varepsilon^{(j)} = \frac{\left\| C_{exp}^{(j)} - C_{ang}^{(j)} \right\|}{\left\| C_{exp}^{(j)} \right\| + \left\| C_{ang}^{(j)} \right\|} \in [0,1] \quad (10)$$

Where || || is the l^2 norm

2.3 Methods of determination IP and AP

2.3.1 Method A: optimization of all inertia I_1, I_2, I_3 and I_4

Considering that the residual is null, (7), (8), and (9) become

$$\sum_{j=1}^{q-1} I_j \ddot{\theta}_j\,(t_i) = C(t_i) + \sum_{j=1}^{q-1} M_j(t_i) \quad (11a)$$

or

$$\sum_{j=1}^{q-1} I_j \dot{\theta}_j\,(t_i) = \int_{t_0}^{t_i} \left(C(s) + \sum_{j=1}^{q-1} M_j\,(s) \right) ds \quad (11b)$$

or

$$\sum_{j=1}^{q-1} I_j\big(\theta_j(t_i)-\theta_j(t_0)\big) = \int_{t_0}^{t_i}\int_{t_0}^{u}\left(C(s)+\sum_{j=1}^{q-1} M_j(s)\right)dsdu \tag{11c}$$

As the method used in Section 2.2 to determine α_4 , for Eq. (9), the double derivative of angles is not used for (11c),
but only values of these angles.

Each equation (11) is equivalent to determine I_1, I_2, I_3 and I_4 such that

$$\forall i, \sum_{j=1}^{q-1} A_{i,j} I_j = B_i \tag{12}$$

where $A_{i,j}$ and B_i are known. Theses equations are equivalent to the overdetermined linear system

$$AI = B, where\ I = \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} \tag{13}$$

which has no solution in the general case, but has a least square sens solution. In this case, the number $j \in \{0, 1, 2\}$ is called the degree of the method A; the number $\varepsilon^{(j)}$, defined by (10) is denoted $\varepsilon_A^{(j)}$ and the coefficient of multiple determination for the overdetermined system (13) is denoted $R_A^{2(j)}$.

2.3.2 Method B: optimization of inertia I4 only

It can be assumed that I_1, I_2 and I_3 are determined in [11]. Then (7), (8), or (9) can be written under the following form: for all i ,

$$I_q - 1\ddot{\theta}_{q-1}(t_i) = -\sum_{j=1}^{q-2} I_j \ddot{\theta}_j(t_i) + C(t_i) + \sum_{j=1}^{q-1} M_j(t_i) \tag{14a}$$

$$I_q - 1\dot{\theta}_{q-1}(t_i) = -\sum_{j=1}^{q-2} I_j \dot{\theta}_j(t_i) + \int_{t_0}^{t_i}\left(C(s)+\sum_{j=1}^{q-1} M_j(s)\right)ds \tag{14b}$$

or

$$I_{q-1}\big(\theta(t_i)-\theta_{q-1}(t_0)\big) = -\sum_{j=1}^{q-2} I_j\big(\theta_j(t_i)-\theta_j(t_0)\big) + \int_{t_0}^{t_i}\int_{t_0}^{u}\left(C(s)+\sum_{j=1}^{q-1} M_j(s)\right)dsdu \tag{14c}$$

Here, it is also equivalent to find I_4 such that

$$\forall i,\ y_i = I_4 x_i. \qquad (15)$$

As previously, we consider $\varepsilon_B^{(j)}$ and $R_B^{2(j)}$.

2.2.3 Method C: values of inertia I1, I2, I3 and I4 according to Winter coefficients

The values of I_1, I_2, I_3 and I_4 are estimated from [11]. As previously, we consider $\varepsilon_C^{(j)}$ and $R_C^{2(j)}$. This method is not an optimization method and $R_C^{2(j)}$ is formally defined; this number is not necessarily positive.

To summarize, we have three methods defined by $X \in \{A, B, C\}$ and for each of them the order j belongs to $j \in \{0, 1, 2\}$. The method X with degree j is called method « Xj ». For example « A2 » is the method A with degree 2. For each of these three methods and for each degree j are defined $\varepsilon_C^{(j)}$ and $R_C^{2(j)}$. An accurate method corresponds to $\boldsymbol{\varepsilon}$ close to 0 and R^2 close to 1.

2.4 Statistics

Main effects of the three methods and the three degrees based on ”residual error” were tested to significance with a general linear model one way ANOVA for repeated measures. When a significant F value was found, post-hoc Tukey tests were applied to establish difference between methods (significant level $p < 0.05$). All analyses were proceeding through the R software [46].

3. Results

The results compared the methods defined by $X \in \{A,B,C\}$ and degree $j \in \{0,1,2\}$ and called “Xj”. Values of $\mathrm{Log10}(\varepsilon)$ and $\mathrm{Log10}(1-R^2)$ are given in tables 1 and 2.

Table 1. Groups statistics of $\mathrm{Log}_{10}(\varepsilon)$ for the three studied methods with the three degrees: mean ± standard deviation

degree j	method A	method B	method C
0	-0.46 ± 0.16	-0.35 ± 0.14	-0.28 ± 0.1
1	-1.06 ± 0.29	-0.59 ± 0.3	-0.37 ± 0.25
2	-1.83 ± 0.44	-1.01 ± 0.38	-0.49 ± 0.33

Table 2. Groups statistics of $Log_{10}(1-R^2)$ for the three studied methods with the three degrees: mean ± standard deviation

degree j	method A	method B	method C
0	-0.27 ± 0.28	-0.05 ± 0.23	0.11 ± 0.24
1	-1.47 ± 0.48	-0.52 ± 0.31	0.03 ± 0.54
2	-2.99 ± 0.73	-1.37 ± 0.56	-0.2 ± 0.82

First of all, taken into consideration the $Log_{10}(\varepsilon)$ and the $Log_{10}(1-R^2)$, the lowest the value, the more accurate the method or the degree of integration.

The general linear model one way ANOVA for repeated measures pointed out significant differences between the three methods (A, B and C) and the three degrees (0, 1 and 2). The post-hoc Tuckey tests indicated that for the methods A and B, the values decreased when the degree increased (degree 2 < degree 1 < degree 0). Concerning the method C, the results were lower for degree 2 than degree 1 and no significant difference was observed between the degree 1 and degree 0.

Comparing the methods, for the degrees 1 and 2, for the both values of $Log_{10}(\varepsilon)$ and $Log_{10}(1-R^2)$, the values were the lowest for method A, then B, then C (A<B<C). With regard to the degree 0, the method A was significantly lower than method B and no difference was observed between the other methods.

Finally, when all methods and degrees were compared together, the lowest values of $Log_{10}(\varepsilon)$ and $Log_{10}(1-R^2)$, were observed for method A2. The later was significantly lower than method A1 and method B2. By comparing A1 and B2, we obtain $p = 0.2719$. The latter were significantly lower than the method B1. Moreover, if we compare B1 to C2 and C2 to C0, we obtain a significant difference. This can be summarized under the following form:

$$A2 < B2 = A1 < B1 < C2 < C0$$

As the results of method A gave unphysical values for inertia, the most accurate method was the method B2. C0 and C2 are the methods with torque value or double integration of torque corresponding to Winter's data respectively. A0 and B0 are optimization methods on all IP or only trunk IP with Winter's data.

4. Discussion

The purpose of this study was to adjust AP and IP of the human segments during squat jumping in order to minimize error in joint torque. The results indicated that the method A2 minimized the most the residual torque (ie. ε and 1-R2) following by the methods B2 and A1 being more accurate than the method B1. Nevertheless, the method A yields unrealistic Ij, therefore the most accurate method retained was the method B2. Consequently, the optimization focused especially on the HAT inertial and anthropometric parameters. It seems to be possible to optimize AP and IP of one segment when the others are known, but the simultaneous optimization of three AP and IP segments seems to be difficult. According to [36] IP and AP optimized for three segments cannot be considered as true, while if two of three segments are known, the IP and AP of the last segment can be calculated.

The IP and AP found with the method B2 are close to the Winter ones but gave better residual joint torque. These differences could be obviously explained by the different position between the subjects performing squat jumps and cadavers. Especially the position of the arms was different, influencing the IP and AP of the HAT segment. [35, 36] used optimization techniques to solve inverse dynamic by determining numerical angles which minimize the difference between the ground reaction force measured and the ground reaction force calculated. They found segmental angles which minimize an objective function under equality and inequality constraints, by taking into account the difference ground reaction force measured and the ground reaction force calculated. From these angles, joint torques are determined. Our approach is different: techniques of [35, 36] to determine angle and torque were not applied. Only experimental displacements smoothed were considered. Then, with a direct inverse method, joint forces and torques were deduced. Finally, an optimization is made on the residual torque and force to determine values of AP and IP. This optimization is very simple and fast, since it is based on the least square linear method. It can be noticed that even if the residual torque or force are minimized, the error at each joint may be increased [35, 36, 37]. However, in our study and for the method B, we only optimized AP and IP of the trunk, consequently the joint torque and forces at the hip, knee and ankle joints remained unchanged. The major difference with classical way is the following point: it is possible to minimize residual torque, or its integral or double integral. The best method corresponds to the minimization of the double integral, which do not use the double derivative of angle.

5. Conclusion

The optimization of inertial and anthropometric parameters seems to be necessary when researchers use inverse dynamic methods. Indeed, cadaver data lead to errors in the calculi of the joint torques, especially in dynamic motions with greater acceleration. These ones could be reduced by optimization methods. The present method of optimization, based on the double integration of residual, has been applied on the HAT segment but could also be applied on more segments.

References

[1] Pearsall, D. J. and Reid, J. G. (1994) The study of human body segment parameters in biomechanics. An historical review and current status report. *Sports Med* **18**, 126-140.

[2] Reid, J. G. and Jensen, R. K. (1990) Human body segment inertia parameters: a survey and status report. *Exerc Sport Sci Rev* **18**, 225-241.

[3] Clauser, C., McConville, I., and Young, I. (1969) Weight, volume and center of mass of segments of the human body. Wright-Paterson A.F.B., Ohio.

[4] Fujikawa, K. (1963) The Center of Gravity in the parts of Human Body. *Okajimas Folia Anat Jpn* **39**, 117-125.

[5] Chandler, R., Snow, R., and Young, J. (1978) Computation of mass distribution characteristics of children. B. Soc. Of Photo-Optical Instrumentation Engineers, Washington.

[6] Hinrichs, R. N. (1990) Adjustements to the segment centre of mass proportions of Clauser et al. 1969. *J Biomech* **23**, 949-951.

[7] Dempster, W. (1955) Space requirements of the seated operator. Techn. Report WADC-TR-55-159. Ohio (WADC-TR- 55-159): Wright-Paterson AFB.

[8] Hinrichs, R. N. (1985) Regression equations to predict segmental moments of inertia from anthropometric measurements: an extension of the data of Chandler et al. 1975. *Biomechanics* **19**, 621-624.

[9] Zatsiorsky, V., and Seluyanov, V. (1983). The mass and inertia characteristics of the main segments of the human body. Champaign: Humain Kinetics.

[10] McConville, J. T., Churchill, T. D., Kaleps, I., Clauser, C. E., and Cuzzi, J. (1980) Anthropometric relationships of body and body segment moments of inertia. Tech. Rep. AFAMRL-TR-80-119, Aerospace Medical Research Laboratory, Dayton, Ohio: Wright-Patterson Air Force Base.

[11] Winter, D. (2009) Biomechanics and Motor Control of Human Movement, fourth ed. John Wiley and Sons, New York.

[12] Yeadon, M. R., and Morlock, M. (1989) The appropriate use of regression equations for the estimation of segmental inertia parameters. *J Biomech* **22**, 683–689.

[13] Durkin, J. (1998) The prediction of body segment paramters using geometric modelling and dual photon absorptiometry. McMaster University: Hamilton, Ontario.

[14] Huang, H. K. and Suarez, F. R. (1983) Evaluation of cross-sectional geometry and mass density distributions of humans and laboratory animals using computerized tomography. *J Biomech* **16**, 821-832.

[15] Martin, P. E., Mungiole, M., Marzke, M. W. and Longhill, J. M. (1989) The use of magnetic resonance imaging for measuring segment inertial properties. *J Biomech* **22**, 367-376.

[16] Pearsall, D. J., Reid, J. G. and Livingston, L. A. (1996) Segmental inertial parameters of the human trunk as determined from computed tomography. *Ann Biomed Eng* **24**, 198-210.

[17] Cheng, C. K., Chen, H. H., Chen, C. S., Chen, C. L. and Chen, C. Y. (2000) Segment inertial properties of Chinese adults determined from magnetic resonance imaging. *Clin Biomech (Bristol, Avon)* **15**, 559-566.

[18] Hatze, H. (2002) Anthropomorphic contour approximation for use in inertial limb parameter computation. In 12th international conference on mechanics in medecine and biology.

[19] Goldberg, E. J., Requejob, P. S. and Fowler, R. G. (2008) The effect of direct measurement versus cadaver estimates of anthropometry in the calculation of joint moments during above-knee prosthetic gait in pediatrics. *J Biomech* **41**, 695–700.

[20] Fowler, E. G., Hester, D. M., Oppenheim, W. L., Setoguchi, Y. and Zernicke, R. F. (1999) Contrasts in gait mechanics of individuals with proximal femoral focal deficiency: Syme amputation versus Van Nes rotational osteotomy. *J Pediatr Orthop* **19**, 720–731.

[21] Pearsall, D. J. and Costigan, P. A. (1999) The effect of segment parameter error on gait analysis results. *Gait Posture* **9**, 173-183.

[22] Lees, A., Rojas, J., Ceperos, M., Soto, V. and Gutierrez, M. (2000) How the free limbs are used by elite high jumpers in generating vertical velocity. *Ergonomics* **43**, 1622-1636.

[23] Lees, A., Vanrenterghem, J. and De Clercq, D. (2004) The maximal and submaximal vertical jump: implications for strength and conditioning. *J Strength Cond Res* **18**, 787-791.

[24] Bobbert, M. F., de Graaf, W. W., Jonk, J. N. and Casius, L. J. (2006) Explanation of the bilateral deficit in human vertical squat jumping. *J Appl Physiol* **100**, 493-499.

[25] Bobbert, M. F., Casius, L. J., Sijpkens, I. W. and Jaspers, R. T. (2008) Humans adjust control to initial squat depth in vertical squat jumping. *J Appl Physiol* **105**, 1428-1440.

[26] Laffaye, G., Bardy, B. G. and Durey, A. (2005) Leg stiffness and expertise in men jumping. *Med Sci Sports Exerc* **37**, 536-543.

[27] Laffaye, G., Bardy, B. G. and Durey, A. (2007) Principal component structure and sport-specific differences in the running one-leg vertical jump. *Int J Sports Med* **28**, 420-425.

[28] Domire, Z. J. and Challis, J. H. (2007) The influence of squat depth on maximal vertical jump performance. *J Sports Sci* **25**, 193-200.

[29] Domire, Z. J. and Challis, J. H. (2010) An induced energy analysis to determine the mechanism for performance enhancement as a result of arm swing during jumping. *Sports Biomech* **9**, 38-46.

[30] Cheng, K. B. (2008) The relationship between joint strength and standing vertical jump performance. *J Appl*

Biomech **24**, 224-233.

[31] Hara, M., Shibayama, A., Arakawa, H. and Fukashiro, S. (2008) Effect of arm swing direction on forward and backward jump performance. *J Biomech* **41**, 2806-2815.

[32] Wilson, C., Yeadon, M. R. and King, M. A. (2007) Considerations that affect optimised simulation in a running jump for height. *J Biomech* **40**, 3155-3161.

[33] Haguenauer, M., Legreneur, P. and Monteil, K. M. (2006) Influence of figure skating skates on vertical jumping performance. *J Biomech* **39**, 699-707.

[34] Vanrenterghem, J., Lees, A., Lenoir, M., Aerts, P. and De Clercq, D. (2004) Performing the vertical jump: movement adaptations for submaximal jumping. *Hum Mov Sci* **22**, 713-727.

[35] Riemer, R. and Hsiao-Wecksler, E. T. (2008) Improving joint torque calculations: Optimization-based inverse dynamics to reduce the effect of motion errors. *J Biomech* **41**, 1503–1509.

[36] Riemer, R. and Hsiao-Wecksler, E. T. (2009) Improving Net Joint Torque Calculations Through a Two-Step Optimization Method for Estimating Body Segment Parameters. *J Biomech Eng.* **131**, 011007

[37] Kuo, A.D. (1998) A Least-Squares Estimation Approach to Improving the Precision of Inverse Dynamics Computations. *ASME J Biomech. Eng* **120**, 148–159.