

IDENTIFICATION OF INTERNAL LOADS AT THE SELECTED JOINTS AND VALIDATION OF A BIOMECHANICAL MODEL DURING PERFORMANCE OF THE HANDSPRING FRONT SOMERSAULT

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Abstract: The handspring front somersault in pike position is analyzed in this paper. The computations have been based on a three-dimensional model of the human body defined in natural coordinates. The time histories of net muscle torques and internal reactions at the ankle, knee, hip and upper trunk-neck joints have been obtained after the solution of the inverse dynamics problem. The sagittal, frontal and transverse plane components of selected net muscle torques and internal reactions are presented and discussed in the paper. It has also been demonstrated that natural coordinates provide a useful framework for modelling spatial biomechanical structures.

Key words: Biomechanics, Modelling, Natural Coordinates, Internal Loads, Somersault

1. INTRODUCTION

There are several hundred classified bounds in men's artistic gymnastics. BlaniK jump is the only one among them associated with the name of a Polish athlete. It is reasonable then that this jump deserves biomechanical identification by domestic researchers. Since none of Polish gymnasts is currently able to perform BlaniK jump effectively, numerical simulations remain the basic tool to investigate this jump. The valuable input data for such simulations can be obtained through a dynamic analysis of the handspring front somersault, which differs from BlaniK jump for one revolution only in the airborne phase.

The first aim of this paper is thus to identify internal and external loads when performing the handspring front somersault.

The second aim is to validate a 3D biomechanical model of the human body, defined in natural coordinates, used earlier in the biomechanical analyses of a long jump (Czaplicki et al., 2006), and a backward somersault from the standing position (Czaplicki, 2009). The handspring front somersault gives an opportunity to verify this model in a movement with two support phases and external loads acting on lower and upper extremities, respectively.

2. BIOMECHANICAL MODEL

The kinematic structure of the biomechanical model is defined in natural coordinates. It is composed of 33 rigid bodies originating from the pelvis in open chain linkages (Fig. 1). The rigid bodies that form the neck, arms, forearms, thighs, shanks, upper torso (numbers in circles from 19 to 25) and the lower torso (numbers 6, 7, 8) are defined by the Cartesian coordinates of two points and one unit vector each. The hands, feet and the head are defined by the coordinates of three points and one unit vector. The complete set of rigid bodies is described by means of 25 points and 22 unit vectors, accounting for a total number of 141 natural coordinates.

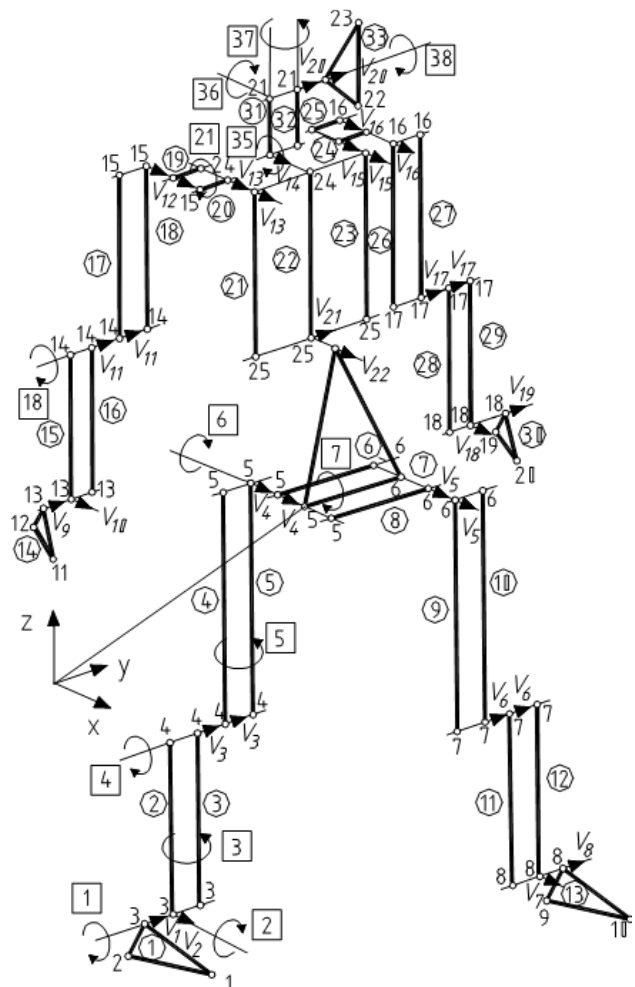


Fig. 1. Biomechanical model of the human body

The biomechanical model comprises revolute and universal joints only. The latter ones are situated in the ankle, the radioulnar

articulations, between the 12th thoracic and 1st lumbar vertebrae (the lower-upper torso joint), and between the 7th cervical and 1st thoracic vertebrae (the upper torso-neck joint).

The model has 44 degrees-of-freedom. Thirty eight of them are attributed to rotations about the revolute and universal joints (Czaplicki et. al, 2006; Czaplicki, 2009a,b). The remaining 6 degrees-of-freedom are from the translational and rotational motion of the pelvis (Fig. 1), which is treated as the base body. The degrees-of freedom discussed in the paper are shown in Fig. 1 (numbers in squares) demonstrating the way they have been defined.

In order to solve the inverse dynamics problem each degree-of-freedom of the biomechanical model has been associated with appended driving constraints of the dot product type (Nikravesh, 1988). An example of these constraints, coupled to 18th degree-of-freedom, is illustrated in Fig. 2.

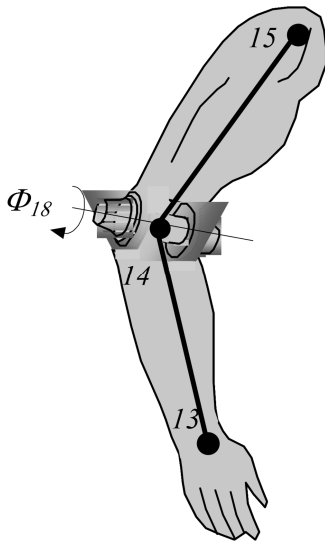


Fig. 2. Driving constraints associated with the right elbow joint

The driving constraints for the right elbow joint are defined as follows:

$$\Phi_{18} = \mathbf{r}_{14,13}^T \mathbf{r}_{14,15} - |\mathbf{r}_{14,13}| |\mathbf{r}_{14,15}| \cos(\psi_{18}(t)) = 0, \quad (1)$$

where $\psi_{18}(t)$ is the angle between vectors $\mathbf{r}_{14,13}$ and $\mathbf{r}_{14,15}$, and its time characteristic is known from kinematic measurements. The complete set of driving constraints is presented in the work of Czaplicki (2009a).

It is necessary to underline that only the key features of the biomechanical model have been discussed. The explanation of double rigid bodies arrangement of most anatomical segments, their inertial properties, and rigid body constraints are described in (Czaplicki et. al, 2006; Czaplicki, 2009a,b), and Garcia de Jalón and Bayo's textbook (1993).

3. INVERSE DYNAMICS

All the constraints, including the appended ones (Fig. 2), can be written in the generic form:

$$\Phi(\mathbf{q}) = \mathbf{0}, \quad (2)$$

where vector \mathbf{q} contains the coordinates of the basic points, the components of the unit vectors, and the angles associated with

degrees-of-freedom of the biomechanical model.

The set of nonlinear equations (2) can be solved iteratively by means of Newton-Raphson method:

$$(\Phi_q^T \Phi_q)_i (\mathbf{q}_{i+1} - \mathbf{q}_i) = -(\Phi_q^T)_i (\Phi)_i, \quad (3)$$

where $(\Phi_q^T)_i$ denotes the Jacobian matrix of the constraints at iteration i . The least square approach is needed since the number of the constraints exceeds the number of natural coordinates.

After computing the coordinates of basic points and unit vectors, the velocities and accelerations of natural coordinates are obtained by differentiating Eq. (2) with respect to the time:

$$\Phi_q \dot{\mathbf{q}} = \mathbf{0} \Rightarrow \Phi_q \ddot{\mathbf{q}} = -\dot{\Phi}_q \dot{\mathbf{q}}. \quad (4)$$

The dynamic equations of the motion for the biomechanical model can be expressed as:

$$\mathbf{M} \ddot{\mathbf{q}} = \mathbf{Q} - \Phi_q^T \boldsymbol{\lambda}, \quad (5)$$

where \mathbf{M} denotes the mass matrix of the system, the vector of accelerations, \mathbf{Q} the vector of external loads containing the gravitational forces and reactions from the ground, and $\boldsymbol{\lambda}$ is the vector of Lagrange multipliers associated with the constraints forces and net driving torques at the joints.

Having known the accelerations from (4), equation (5) can be solved for the Lagrange multipliers.

4. DATA ACQUISITION

A twenty-three-year-old member of Polish women's olympic gymnastics team, with the height of 163 cm and a body mass of 53 kg, performed several handspring vaults with a front somersault in pike position. One of the trials was chosen as the most representative and subjected to the identification. The key phases of the investigated jump have been depicted in Fig. 3. The upper pictures show the configuration of the athlete's body at the beginning and at the end of the first support phase, whereas the lower ones indicate the body position at the moment of touching the gymnastic table and after one revolution in the air.



Fig. 3. Handspring front somersault in pike position

The body motion kinematic data were simultaneously recorded by 4 synchronized cameras (Fig. 3) working at the sampling

frequency of 100 Hz. The positions of the 23 anatomical points required to reconstruct the motion of the biomechanical model were digitized in APAS package environment. The remaining stages of data acquisition process as well as handling the raw kinematic data were similar to those described elsewhere (Czaplicki, 2009a,b).

The external reactions acting on the athlete's body during support phases were not measured directly. Instead, they were obtained using Newton-Euler iterative scheme starting from the top-most segment. This procedure in natural coordinates can only be applied if Lagrange multipliers have been known earlier. A planar model of the human body (Blajer et al., 2010) was therefore used to calculate the vertical and horizontal ground reaction forces in the sagittal plane during the contact of the feet with the springboard and the hands with the gymnastic table. The medial-lateral component of the ground reaction force was calculated through optimization designed for minimizing the difference between recorded and computed trajectory of the jumper's centre of mass in the frontal plane.

The centre of pressure path during the support phases was determined using a Kistler force plate (Fig. 4), which measured two coordinates of the path while the athlete imitated the positions recorded when performing the jump.

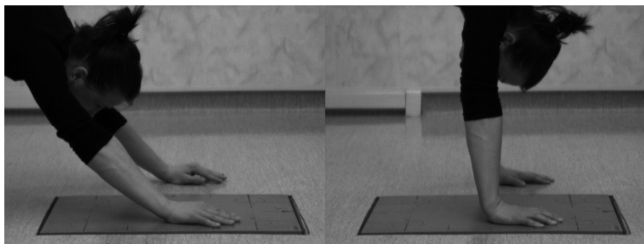


Fig. 4. Measuring the centre of pressure path for the hands

5. RESULTS AND DISCUSSION

The time histories of the component moments associated with the first, fourth and seventh degrees-of-freedom are depicted in Fig. 5. They represent the flexion or extension action of the muscles at ankle, knee, and hip joint. All the characteristics possess a clearly recognized contact phase with the springboard between 0.17 and 0.28 s. The component moment at a hip joint reaches the highest values and its negative sign indicates the action of hip extensors. The sudden change of the value of this moment to the level of -600 Nm, and other moments to the level of 200 Nm reflects the impact of the ground. The impact must be absorbed through the tendons and passive joint structures (ligaments), since the muscles are not able to generate large moments in such short periods of time (Bobbert and Zandwijk, 1999). A double peak shape of most characteristics is due to the drift of the centre of pressure as well as to large friction force at the initial contact, which is also induced by a slight slope of the springboard towards the feet. The remarkable values of the component moments about the medial-lateral and vertical axis suggest that the planar analysis of the investigated vault can produce a systematic error. It would be particularly evident for the torques at the knee and ankle joints.

The characteristics of horizontal, medial-lateral, and vertical reactions in the right leg joints are presented in Fig. 6. The damping effect of the vertical reaction between the ankle joint and the

hip joint is evident. The highest value of this reaction during contact with the springboard reaches 2400 N in the ankle joint whereas about 1500 N in the hip joint. Since small inertia effects originating from the foot can be neglected, the shape of the internal reactions in the ankle joint reflects explicitly (with the opposite sign) the profiles of the ground reaction components.

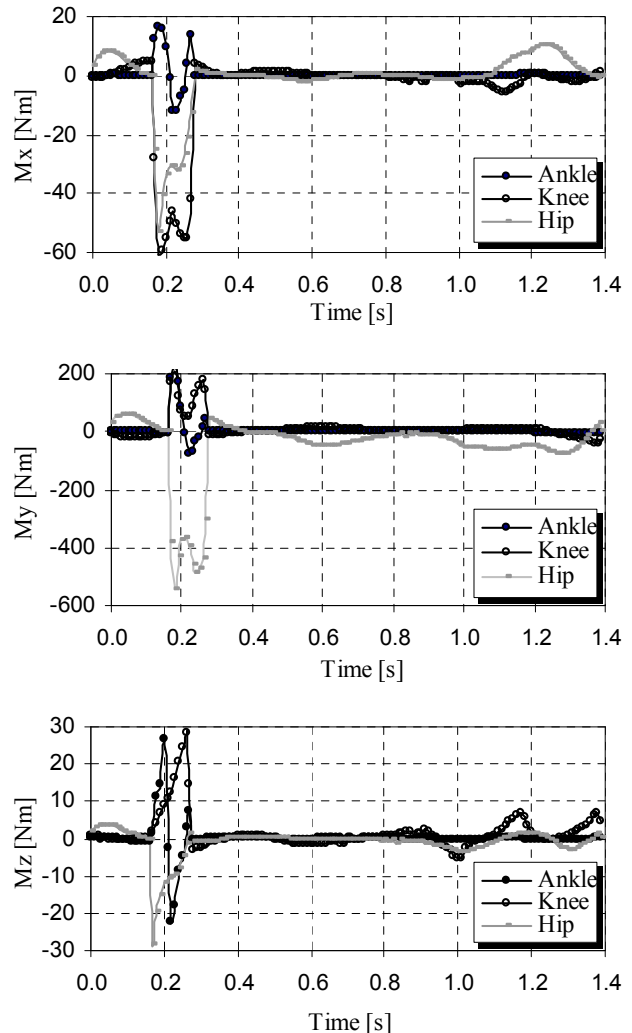


Fig. 5. Component moments associated with the 1st, 4th and 7th degrees-of-freedom

The time courses of the component moments attributed to the 21st degree-of-freedom are presented in Fig. 7. They can be identified with the movement of the arm in the sagittal plane. The highest values of the component moment (M_y) about medial-lateral axis reach the level of 60 Nm pointing out the second support phase when the hands get in touch with the gymnastic table. Low values of the other components during the jump show that the arm movement takes place firmly in the sagittal plane.

Fig. 8 presents the time histories of component moments associated with the 35th degree-of-freedom, which reflect the neck movements with respect to the trunk in the sagittal plane. The significant domination of the medial-lateral component moment is clearly visible. The peak values of this parameter occur just before the first support phase to ensure the proper orientation of the body with respect to the springboard, and after body grouping in the airborne phase to keep the head aligned with the trunk.

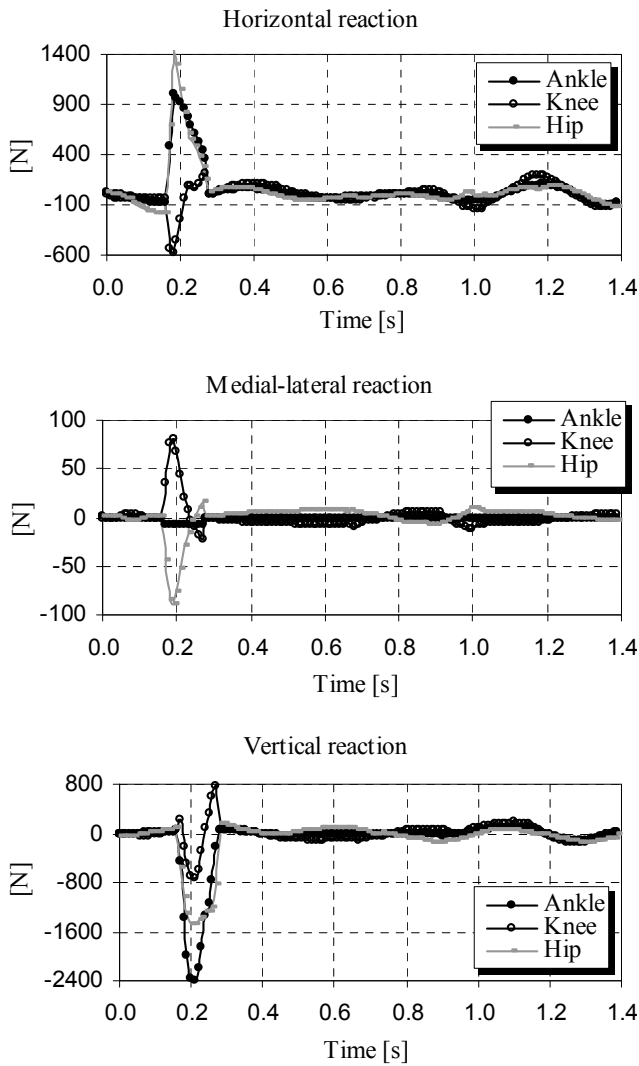


Fig. 6. Internal reactions in the joints of the right leg

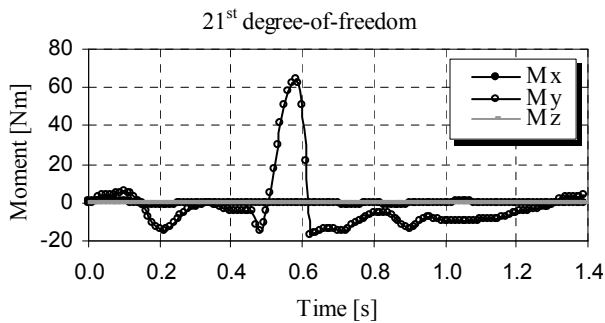


Fig. 7. Component moments associated with the 21st degree of freedom

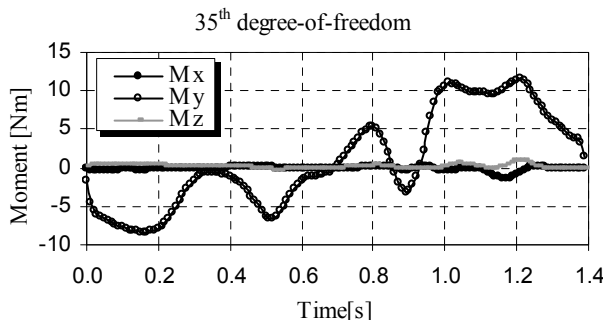


Fig. 8. Component moments associated with the 35th degree of freedom

A 3D state of loads at the neck-head joint, rarely described in the biomechanics literature, is shown in Fig. 9.

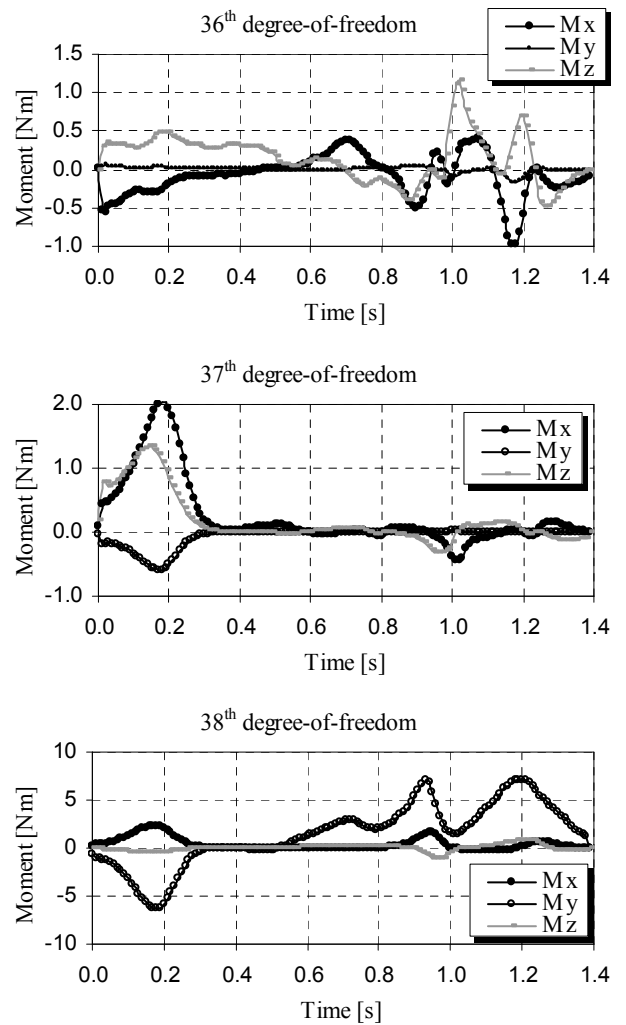


Fig. 9. Component moments associated with the 36th, 37th and 38th degrees-of-freedom

The time characteristics of component moments related to the 36th, 37th and 38th degrees-of-freedom represent side bending of the head in the frontal plane, rotation of the head with respect to the neck in the transversal plane, and flexion/extension of the head in the sagittal plane, respectively. The largest values are achieved in the sagittal plane by the component moment connected with the 38th degree-of-freedom. The time course of this component is similar to the already discussed characteristics of the upper trunk-neck joint and again, its significant domination over the other components can be easily recognized. The component moments associated with the 36th and the 37th degrees-of-freedom reach low values not exceeding the level of 2 Nm.

6. CONCLUSIONS

The work has been focused on the loads' identification in the leg, shoulder and other joints when performing the handspring front somersault in the pike position. The obtained time courses of torques and internal reactions in the joints have, apart from cognitive reasons, a clear interpretation, reflecting a distinctly impulsive character of movement during the contact with the

springboard and gymnastic table, and the nature of the other phases of the vault.

The highest values of the internal loads are in the first support phase. The net muscle torque at the hip joint reach then the level of -600 Nm whereas the internal vertical reaction in the ankle joint is about 2400 N. The maximum value of the net muscle torque at the shoulder joint is one order of magnitude lower reaching the level of 60 Nm in the second support phase.

The knowledge of load characteristics in the joints during the analyzed vault can be of interest to both athletes and gymnastics coaches.

A three-dimensional model of the human body defined in natural coordinates turned out to be effective in full rotations of individual parts of the body, and during the contact of the upper extremities with the ground. The latter aspect of the model has been checked for the first time.

Inverse simulations with different body positions just before the contact with the springboard and gymnastic table seem to be necessary in order to answer the question if a proper body configuration during both support phases influences the loads' reduction in the joints. If so, the research will gain another practical quality, since its results can help to reduce the risk of injuries.

Forward simulations with changing initial conditions, as those described by Wilson et al. (2011), are also needed to check how such perturbations can influence the quality of the vault. There is a place within these simulations to analyze Blanik vault. The authors of this work are convinced that the presented results will be helpful to complete this task. However, knowing the specificity of integration in natural coordinates (Czaplicki, 2007) a 2D approach ought to be recommended for starting the simulations.

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