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Modelling and analysis of lower limb joint loads during the Naeryo chagi technique in taekwondo

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Summary

Study aim: estimate reaction forces and muscle torque in lower limb joints during the Naeryo chagi technique in taekwondo.
Material and methods: the parameters of the Naeryo chagi kick were measured with a Vicon motion tracking system comprising ten MX T40S cameras, two reference cameras and four AMTI BP600900-2000 force plates. Additional measurements were performed using the BTS-4AP-2K force analysis system equipped with a WB-4AP punching bag. The acquired raw data were processed and synchronized using Matlab v.R2007a software. A computer simulation created on the basis of the adopted mathematical model was used to identify reaction forces and control moments.
Results: the highest joint loads occurred at the moment when the striking leg reversed its movement direction from rising to rapidly falling towards the target. The knee and ankle joints of the supporting leg were subject to greatest reaction forces and muscle torque.
Conclusions: it is recommended to follow an exercise routine aimed at strengthening and stabilizing the structures of motor system subject to the greatest load.

Keywords: Taekwondo – Joint loads – Naeryo chagi – Vicon system

Introduction

A combat sports technique used for the purposes of both offense and counterattack is the Naeryo chagi technique. The technique is most commonly used for striking an opponent's head. In a combat sports encounter, the technique is usually executed in one of two ways: either using the rear leg with the foot launched directly towards the opponent's head, or with the lead (front) leg after closing the distance to an opponent. Analyses of kinematic parameters, i.e. reaction time and movement time, as well as kinaesthetic parameters, i.e. ground reaction force of the Naeryo chagi kick performed with the front leg, were described in Tsai et. al [8]. Based on the results of their measurements, the authors recommended improving the flexibility and force of lower limbs through training. A study conducted by Wąsik [11] suggested a division of the Naeryo chagi technique executed with the rear leg into four phases, and compared their respective duration. Additionally, the study examined the velocity components of the foot of the striking leg. Similar results and conclusions were also indicated in a study published by Bercades and Pieter [1]. There, the authors report that the speed of the foot of the striking leg is similar for both styles of executing the technique.

In order to analyse joint reaction forces during certain motor activities in a non-invasive way, most studies utilize methods of computer simulation using a specific dynamic model that accounts for the geometric and mass properties of the human musculoskeletal system and the biomechanics of movement. The input data for such computer simulations comes from measurements of the kinematic properties of the analysed movements obtained through various photogrammetric methods [4].

The load forces exerted on the motor system during the taekwondo Ap chagi technique and the karate Mae geri technique were presented in a study by Czaplicki [5, 6]. No similar studies of the Naeryo chagi technique were found in the literature.

The purpose of this study was to estimate the joint reaction forces and total muscle force torque during the Naeryo chagi technique.

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Material and methods

A 25-year-old athlete belonging to the Olympic taekwondo club AZS AWF in Warsaw participated in the study. The athlete was a second-degree black belt experienced in national and international competitions. The athlete was 170 cm tall, his body weight was 63 kg, and he was right leg dominant. The measurements were performed on a Vicon system consisting of four AMTI BP600900-2000 force plates, ten MX T40S cameras with frequency of 250 Hz, two Bonita reference cameras, a Giganet power supply unit, and Nexus v. 1.8.1 and Polygon v. 2.1. software. The impact force of the kick was measured using the BTS-4AP-2K system (JBA, Zbigniew Staniak) equipped in a specially fitted accelerometric punching bag WB-4AP.

The athlete performed a series of five Naeryo chagi kicks with each leg. The average execution time, which was measured from the moment the striking foot took off from the force plate to the moment it rested again on the platform, was equal to 1.2 seconds; analysis therefore covered 300 frames of video (registered with 250 Hz frequency). The joint reaction forces were analysed using a smaller section of the recording, which consisted of 200 frames. This allowed for a closer examination of the most important phases of performing the kick, such as the strike out phase and the moment of contact with the target. Due to the fact that the final phase of the kick, in which the striking leg returns to its starting position, was not consistent across all attempts, this section of the recordings was not analysed. The specific point in time used for synchronizing all of the recordings was the moment in which the striking foot connected with the punching bag, marked as frame no. 150. The acquired data was synchronized and smoothed with Matlab v. R2007a software (third degree spline functions), and the mathematic model used for calculations was implemented.

The biomechanical model

The assumed model of the entire human body consisted of 14 elements; however, only the lower limb joints were subject to analysis. Regression equations [12] were used in the modelling process in order to determine the geometric and mass data of individual segments of the model based on the known anthropometric data. In following the modelling methodology as suggested by Blajer et al. [2–4], the proposed model was designed as a planar kinematic construction composed of $N = 14$ elements open-chain whose segments, represented as rigid bodies, were linked together by $k = 13$ ideal hinge joints. The model has 13 degrees of freedom. The external loads exerted on the model come from the gravitational forces affecting its segments, control in the joint hinges, as well as other external reactions resulting from contact with the surroundings, e.g. ground reaction forces (Figure 1).

Equations of motion in absolute coordinates

Dynamic equations of system motion formulated in $n = 3N = 42$ absolute coordinates $p = [x_1, y_1, \varphi_1, \ldots, x_{14}, y_{14}, \varphi_{14}]^T$, representing the coordinates of the centres of mass of the individual segments and their angular orientation in an inertial frame of reference, take the following form:

$$M\ddot{p} = f - C^T\lambda - C_r^T\lambda_r + Bu \tag{1}$$

where: $M\ddot{p} = f$ are the dynamic equations in p of independent segments (they are affected only by gravitational forces), $M = \operatorname{diag}(M_1, \ldots, M_{14}) = \operatorname{diag}(m_1, m_1, J_{C1}, \ldots, m_{14}, m_{14}, J_{C14})$ is a generalized mass matrix, $f = [f_1^T, \ldots, f_{14}^T]^T$ is a vector of generalized gravitational forces, where

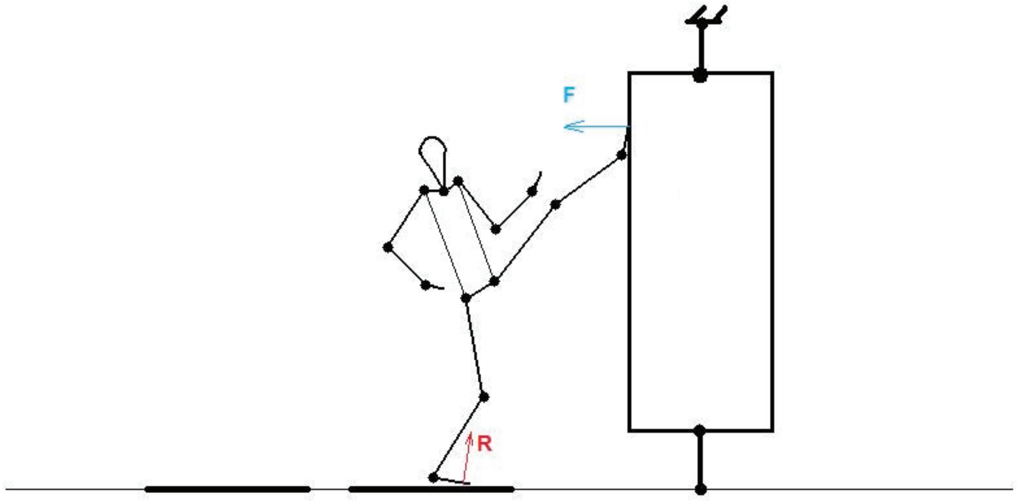


Fig. 1. Scheme of the experiment

$f_i = [F_{ix}, F_{iy}, M_{Ci}]^T$, and hence $f = [0, -m_1g, 0, \ldots, 0, -m_{14}g, 0]$. m_i and J_{Ci} denote the mass and the central mass moment of inertia of a particular segment of the model, whereas g is the gravitational acceleration. The motion of the segments is also affected by joint reaction forces, ground reaction forces, and system control. Passive forces generated by the musculotendon connections (joint reaction forces) are represented by the vector of generalized reaction forces $f_\lambda = -C^T\lambda$, where C is the matrix of tendons and defined by $C = \partial\Phi/\partial p$, while $\lambda = [\lambda_1, ..., \lambda_m]^T$ is the vector of vertical and horizontal components of the joint reaction forces. The Matrix C has dimensions m × n, in which $m = 2k = 26$ corresponds with the number of equations of tendon connections in the joints $\Phi(p) = 0$. The assumed deterministic (simplified) model uses $k = 13$ resultant muscle force torque $u=[\tau_1, ..., \tau_{13}]^T$, represented by vector $f_u = Bu$, where B is the distribution matrix of control parameters. The vector of generalized ground reaction forces modelled using $m_r = 3$ components $\lambda_r = [R_x, R_y, M_p]^T$ reduced to point P takes the form of $f_r = -C_r^T\lambda_r$, where matrix C_r of component distribution λ_r in directions p with dimensions $n \times m_r$ (42 × 3), was formulated according to [3].

Equations of motion in independent coordinates

The formulated dynamic equations of motion in directions $n = 42$ of the absolute coordinates p were transformed into $r = 16$ independent coordinates $q = [x_0, y_0, \varphi_1, \varphi_2, \varphi_3, \ldots, \varphi_{14}]^T$, where x_0 and y_0 are the absolute coordinates in a global coordinate system. Point 0 is located on the segment modelling the trunk, exactly half the distance between points H_P and H_L representing the axis of rotation of lower limb hip joints (Figure 2b). The coordinates $\varphi_1, \ldots, \varphi_{14}$ represent the angles denoted by p which position individual segments in relation to the vertical.

In order to determine the reaction forces developed between segments, it is necessary to input the coordinates $m = 26$ of tendons $z = [z_1, ..., z_{26}]^T$ thus indicating the constrained vertical and horizontal movements (Figure 2a). The complex form of dependence $p = g(q)$ equals $z = \Phi(p) = 0$, and is validated after introducing q, i.e.: $\Phi(g(q)) \equiv 0$.

The simplified form of joint hinges can be expanded to the following form: $p = g(q,z)$. Its derivation according to time leads to:

$$\dot{p} = \left(\frac{\partial g}{\partial q}\right)_{z=0} \dot{q} + \left(\frac{\partial g}{\partial z}\right)_{z=0} \dot{z} = D(q)\dot{q} + E(q)\dot{z} \qquad (2)$$

Matrix D with dimensions n × r (42 × 16) is an orthogonal compensation matrix of the tendon matrix C, the dependences between matrices C and D are the following: $CD = 0 \Leftrightarrow C^TD^T = 0$. In turn, n × m (42 × 26) dimensional matrix E is a pseudo-inverse matrix of C: $CE = E^TC^T = I$, where I is a m × m (26 × 26) dimensional unit matrix.

After solving the simplified equations of joint hinges and substituting p, $\dot{p}$, and $\ddot{p}$ respectively with $p = g(q)$, $\dot{p} = D(q)\dot{q}$, $\ddot{p} = D(q)\ddot{q} + \gamma(q, \dot{q})$ representing equations defining the dependences between absolute coordinates p and independent coordinates q at the position, velocity and acceleration levels, the equations of motion in independent coordinates take the following form:

$$\bar{M}(q)\ddot{q} + \bar{d}(q, \dot{q}, t) = \bar{f}(q, \dot{q}, t) + \bar{B}(q)u - \bar{C}_r^T(q)\lambda_r \qquad (3)$$

where $\bar{M} = D^TMD$ is the matrix of generalized mass, $\bar{d} = D^TM\gamma$ is the vector of dynamic forces due to centrifugal and Coriolis acceleration, in which γ is an n-dimensional vector, $\gamma = \dot{D}\dot{q}$, $\bar{f} = D^Tf$ is the vector of generalized forces, and $\bar{B} = D^TB$ is the distribution matrix of control parameters u.

Using the above equations of motion in independent coordinates, it is possible to determine the cumulative value of muscle force torque and ground reaction forces with the following dependence:

$$\begin{bmatrix}\lambda_r \\ \tau\end{bmatrix} = [\bar{C}_r^T(q) \vdots \bar{B}(q)]^{-1} (\bar{M}(q)\ddot{q} + \bar{d}(q, \dot{q}) - \bar{f}(q, \dot{q}) \qquad (4)$$

The vertical and horizontal components of joint reaction forces are determined through the following dependence:

$$\lambda(q, \dot{q}, \ddot{q}, t) = E^T(f - C_r^T \lambda_r + Bu - M(D\ddot{q} + \gamma)) \qquad (5)$$

Ethical approval for this study was provided by the Local Ethical Committee, and written informed consent was obtained from participants. The study was performed according to the Declaration of Helsinki.

Results

Changes in kick impact force are displayed in Figure 3.

The maximum value of impact force is higher for kicks delivered with the right leg. The difference was confirmed with a Student's *t*-test for dependent variables ($t = 3.73$, $p < 0.05$). The time to peak force equalled 0.036 seconds in both cases. The impact time on the bag lasted for about 0.072 seconds. The average maximum impact force reached 122.6 ± 14.5 N for kicks delivered with the right leg, and 103.6 ± 15.8 N for kicks delivered with the left leg. Figure 4 displays the values of resultant reaction forces in the hip joint, knee joint, and the ankle joint of the striking and the supporting leg.

From among 13 total muscle force torques governing the motion of the segments of the model, only the values corresponding to lower limb joints are displayed. Figure 5 displays the values of force moments in the hip joint, knee joint, and the ankle joint of the striking and the supporting leg. The progression of changes in

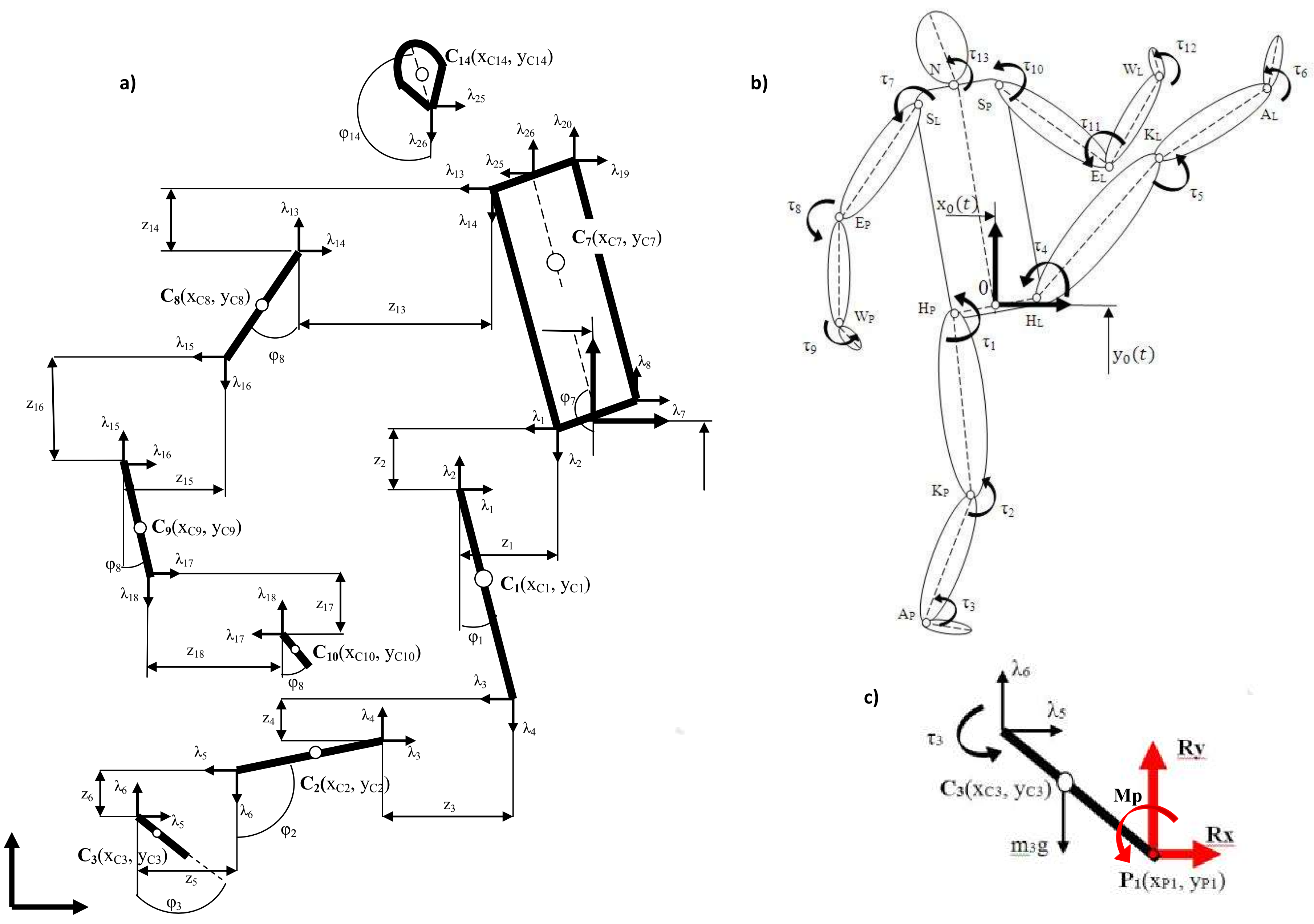


Fig. 2. Assumed model simplifications: a) Coordinates of tendons and joint reaction forces, b) Deterministic control model using control moments, c) Components of ground reaction force

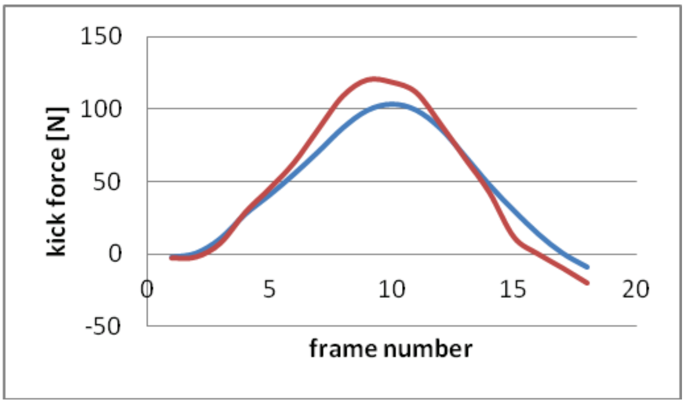
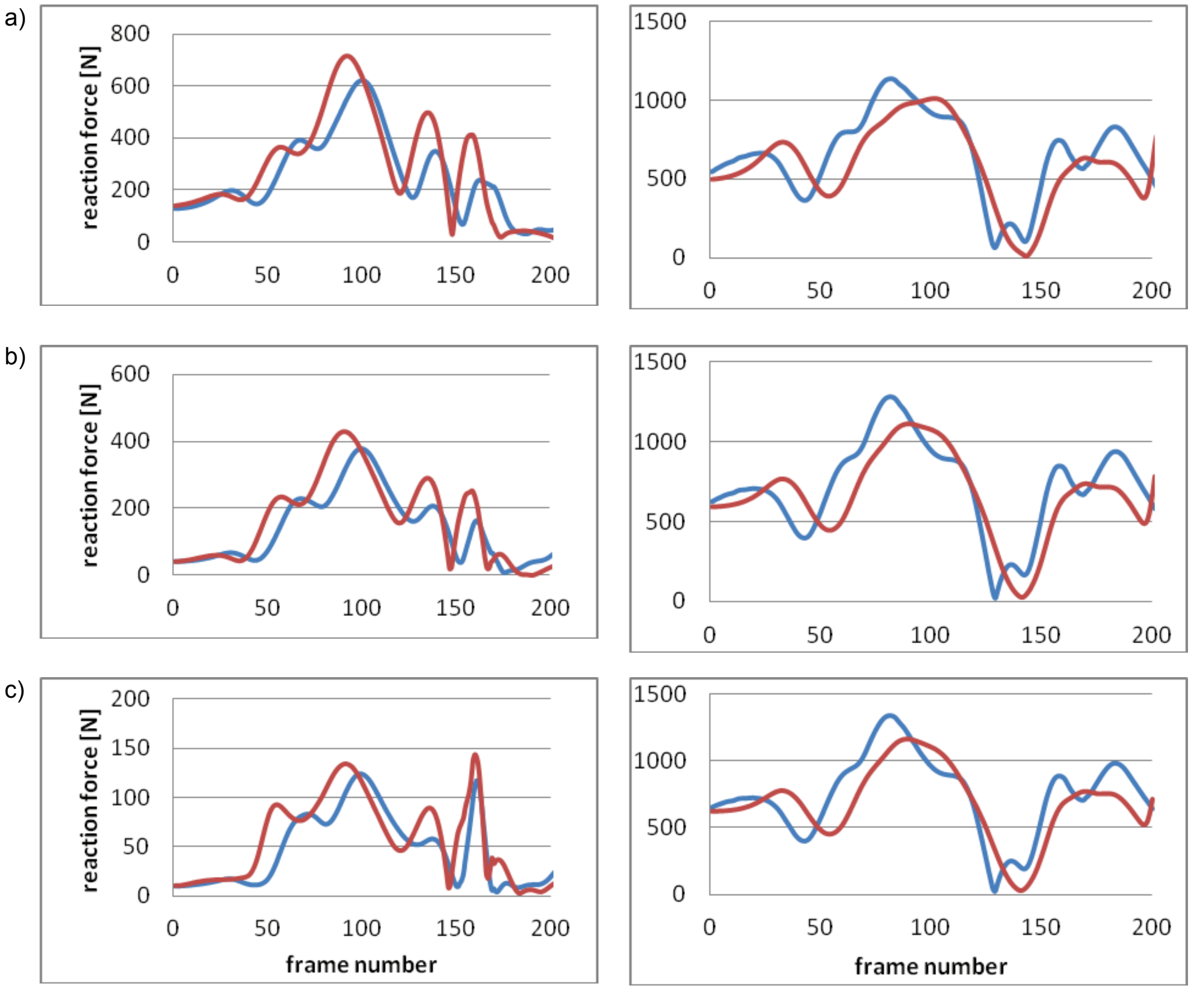


Fig. 3. Changes in kick impact force. Red line – technique performed with the dominant leg; blue line – technique performed with the non-dominant leg

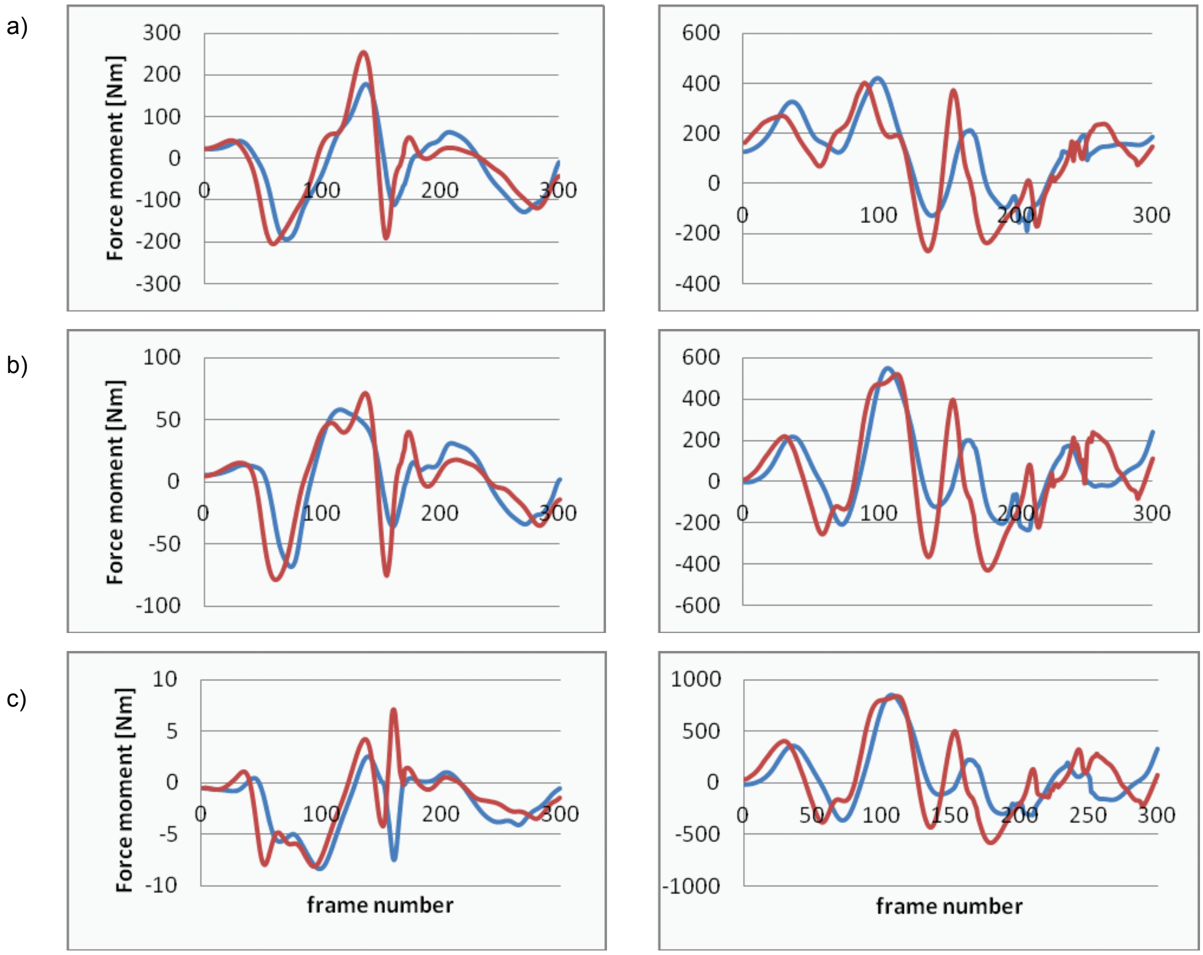


Striking leg

Supporting leg

Fig. 4. Values of resultant reaction forces in the joints of the striking and supporting leg: a) hip joint, b) knee joint, and c) ankle joint. Red line – technique performed with the dominant leg; blue line – technique performed with the non-dominant leg

muscle force torques is similar in the joints of both the striking and the supporting leg. The values of force moments take on more extreme values in the case of kicks delivered with the dominant leg. The values of force moments in the hip and knee joints of the dominant striking leg go through a more dynamic shift around frame 150



Striking leg Supporting leg

Fig. 5. Values of total muscle force torque in the joints of the striking and supporting leg: a) hip joint, b) knee joint, and c) ankle joint. Red line – technique performed with the dominant leg; blue line – technique performed with the non-dominant leg

– the moment of contact with the punching bag, which may yield a greater force of impact. A significant difference in the progression of muscle force torque between the ankle joints of the left and the right striking leg can be observed in frames 150–170, when the impact force is reached and the target is displaced. Positive moment values indicate dorsiflexion of the ankle joint exposing the rear of the heel with which the impact is delivered. Meanwhile, the negative moment values observed in the case of kicks delivered with the left leg indicate action of flexor muscles at the base of the foot. Following the contact of the sole of the foot with the target, the punching bag is further pushed by the plantar flexion movement in the ankle joint. The muscles of the supporting leg also play a role in the technique, which is confirmed by the control moment changing from positive to negative values.

The moment in which the striking foot makes contact with the bag causes a dynamic increase in the resultant reaction forces in the joints of the striking leg, particularly in the ankle joint. Kicks executed with the dominant leg are characterized by more dynamic changes in joint reaction forces of the striking leg than the kicks delivered with the non-dominant leg. The reverse situation occurs in the joints of the supporting leg. Reaction forces in the joints of the supporting leg reach the lowest values immediately before and at the instant of contact with the target. Although the reaction forces observed in the supporting leg are greater than in the striking leg, their changes are not as dynamic. It is likely that the impact force of the kick is dampened by individual segments of the biokinematic chain, including the described joint hinges.

The joint reaction forces in the striking leg and supporting leg, as well as the muscle force torque in the joints of the supporting leg, reach their highest values at the top of the stroke (around frame 100), when the motion of the striking leg reverses and it starts to dynamically fall towards its target.

Discussion

The mechanics of various taekwondo techniques can be analysed using models with different levels of complexity. Wąsik's publications [9, 10] present mathematical models of the studied phenomena that usually consist of only a few equations. The inverse dynamic function, which allows for the estimation of the values of total muscle force torque and reaction forces in taekwondo and karate front kicks, can be found in Czaplicki's publications [5, 6], in which a similar methodology of mathematical modelling is applied. The structure of the kick examined resembles the movement technique described in this paper, and the obtained progression of muscle force torques correlates with the results presented in this paper. The movement techniques described by Czaplicki are considerably easier to perform, which results in an execution time that is twice as short. The supporting leg is subject to the greatest load during the Naeryo chagi technique. The values of control moments in the joints of the supporting leg are greater as it becomes responsible for stabilizing the athlete's entire body. The knee and hip joints are subject to the greatest load and the maximum values of reaction forces reach twice the total amount of body mass. The estimated reaction forces and muscle torque values occur at the top of the stroke, when the striking leg reverses the direction of its movement. This may be due to the fact that a sudden shift in movement direction causes the accelerated mass of individual segments to exert a heavy load on the surface of the joints. Still, the ability to skilfully make use of body mass in the performance of the technique would result in a greater impact force of the kick [7].

According to the observations made in a study by Blajer et al. [4], it should be considered that the processing of measurement data might have distorted the representation of certain phenomena. In spite of this, the presented method can be viewed as a useful tool for determining joint and motor system loads.

Conclusion

The presented method of modelling and analysis of lower limb joint loads during the Naeryo chagi taekwondo technique can be viewed as a useful tool for determining motor system loads. The acquired data suggests that taekwondo practitioners ought to include exercises in their training routines that strengthen and stabilize structures of the motor system subject to the greatest load.

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