

# Application of force-length curve for determination of leg stiffness during a vertical jump

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*Purpose:* The aim of this study was to present the methodology for estimation of a leg stiffness during a countermovement jump. The question was asked whether leg stiffness in the countermovement and take-off phases are similar to each other as demonstrated in previous reports. It was also examined whether the stiffness in left lower limb is similar to the one in right lower limb. *Methods:* The research was conducted on 35 basketball players. Each participant performed three countermovement jumps with arm swing to the maximum height. Measurements employed a Kistler force plate and a BTS SMART system for motion analysis. Leg stiffness (understood as an inclination of the curve of ground reaction forces vs. length) was computed for these parts of countermovement and take-off phases where its value was relatively constant and  $F(\Delta l)$  relationship was similar to linear. *Results:* Mean value ( $\pm$ SD) of total stiffness of both lower limbs in the countermovement phase was  $7.1 \pm 2.3$  kN/m, whereas this value in the take-off phase was  $7.5 \pm 1$  kN/m. No statistically significant differences were found between the leg stiffness in the countermovement and the take-off phases. No statistically significant differences were found during the comparison of the stiffness in the right and left lower limb. *Conclusions:* The calculation methodology allows us to estimate the value of leg stiffness based on the actual shape of  $F(\Delta l)$  curve rather than on extreme values of  $\Delta F$  and  $\Delta l$ . Despite different tasks of the countermovement and the take-off phases, leg stiffness in these phases is very similar. Leg stiffness during a single vertical jump maintains a relatively constant value in the parts with a small value of acceleration.

*Key words:* asymmetry, countermovement jump, elasticity, quasi-stiffness, basketball players

## 1. Introduction

Leg stiffness is a variable that has been used mainly in analyses of human and animal locomotion. Although it might seem to an observer that the body is able to move at a constant velocity, human movement occurs as a result of cyclic propelling moves of lower limbs. This causes that the moving “body” (movement of the centre of mass) is exposed to alternate phases of acceleration and deceleration. Therefore, locomotion of bipedal mammals connected with walking, running, hopping, trotting or galloping resembles the bouncing ball movement. Therefore the term “bouncing gait” has been used to describe locomotion where lower limbs perform the role of springs responsible for movements of the centre of body mass. A spring-mass

model has been employed to describe bouncing gait. The model is comprised of a point that represents the total body mass and the massless lower limb modelled as a spring [5], [9], [10].

Elasticity is a property of macroscopic bodies which consists in ability to recover the previous shape and volume after mechanical forces that cause deformation are removed. The ability to absorb and recover elastic energy in human body is observed in tendino-muscular groups. One example of the tissue that behaves like a spring that absorbs and releases the elastic energy during human locomotion is long and compliant Achilles tendon. It is estimated that the Achilles tendon is able to accumulate 35% of the mechanical energy necessary for performing the running gait [7]. The quantitative measure of body elastic properties is stiffness, which represents the measure of

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resistance to strain. According to equation (1), stiffness ( $K$ ) is the ratio of the value of the cause of the strain ( $\Delta F$ ) to quantitative measure of strain ( $\Delta l$ )

$$K = \frac{\Delta F}{\Delta l}. \quad (1)$$

Elastic energy is also used during locomotion movements performed in stretch-shortening cycle (SSC), for example, vertical jumps (single or cyclic). Performing a countermovement before take-off (lower limbs flexion) leads to the rapid extension of muscles, tendons and other compliance tissues (in lower limbs and trunk) before the contraction, which helps accumulate elastic potential energy and, consequently, doing greater work in the concentric phase. The factor that causes an increase in the work done during a contraction is the phenomenon of tissue elasticity, which reveals during stretch-shortening cycle and the stretch reflex [15], [18]. Thanks to the ability of tendinomuscular groups to absorb and release elastic energy, this energy is added to the contraction work. Too slow (little dynamic) countermovement causes that the elastic energy accumulated during the eccentric phase will be partly dissipated, e.g., in the form of heat [1]. During a vertical jump, the values of potential energy of gravity, elastic and kinetic energy are changed. At the highest point of a jump (during flying phase), potential energy of the gravity is the greatest, whereas potential elastic energy and kinetic energy are equal to zero. During falling down, the kinetic energy of the system increases. Potential elastic energy is an energy determined for the elastically deformed body. Therefore, it can be adopted according to the model presented in Fig. 1 that these deformations occur in the lower limb of a person who performed a vertical jump. The potential energy accumulated during the countermovement phase adds up to the energy supplied by contracting muscles used in the take-off phase. Consequently, the total mechanical energy used during the jump might have higher values. Transformation of this energy during the flying phase in potential energy allows higher jump height to be obtained. Potential elastic energy of the elastic body with linear profile is proportional to the squared strain

$$E_{ps} = \frac{1}{2} \cdot K \cdot \Delta l^2, \quad (2)$$

where  $E_{ps}$  means potential elastic energy,  $K$  is the stiffness, and  $\Delta l$  is the length change.

Leg stiffness is a concept that relates to the limb as a whole system rather than only to tendinomuscular systems. With this approach, leg stiffness depends on

the stiffness of all the compliant tissues such as ligaments, blood vessels or bones [17]. Tendon stiffness is almost constant, whereas muscle stiffness might vary over a broad range. Muscle tension causes the increase in its stiffness and ability to accumulate elastic energy, whereas relaxing the muscle increases susceptibility to deformation [27], [28]. The maximally excited muscle achieves greater stiffness than tendons [27], [28]. It is expected that both relatively high and low values of leg stiffness might lead to injury of soft tissues and joints. Also, magnitude of inter limb asymmetry in leg stiffness may increase the potential injury risk during jumping [12], [20].

Previous studies on leg stiffness have been mainly based on measurements of the ground reaction forces recorded by means of a force plate and measurements of changes in location of the body's centre of mass (COM). Equation (1) is substituted with: maximum value of the ground reaction forces and maximum displacement of COM during body contact with the ground [3], [4], [6], [8]–[10], [12], [16], [20], [21]. Dalleau et al. [6] presented a method to determine leg stiffness during hopping. The method assumed that the curve that describes the relationship between ground reaction force and time is a part of a sine wave. Currently there are several computational methods, but they do not necessarily yield the same values of leg stiffness [3], [4], [13], [23]. However, these methodologies estimate only the apparent or quasi-stiffness and not the true stiffness as it is defined in mechanics [17]. In complex movements, obtaining one value for leg stiffness suggests a relatively constant level of stiffness over its duration. Furthermore, the relationship  $F(\Delta l)$  is not as linear for the lower limb as in the case of an ideal spring. Latash and Zatsiorsky [17] suggest the division of the stiffness into the three groups:

- “stiffness – the measurements are performed at equilibria, resistance to the external force is provided by elastic forces and potential energy is being stored,
- apparent stiffness – the measurements are performed also at equilibria, the physical nature of the resistive forces is being disregarded,
- quasi-stiffness – the measurements are performed not at equilibria” [17] but during transient states.

Therefore, stiffness determined based on the observation made during the movement should be considered as the third group. This means that an accurate description of the research methodologies that allows for determination of what is actually examined is essential. The above division ensures the elimination of the conceptual chaos around stiffness as this concept

has been overused or improperly used also with respect to other body parameters [17]. Only a uniform and reliable measurement methodology offers opportunities to explain still unresolved questions about the relationships between leg stiffness and sport movement performance or injury risk [4], [23].

The aim of this study was to present the methodology for estimation of a leg stiffness during a countermovement jump (CMJ). We attempted to determine value of leg stiffness for the phases of countermovement and take-off separately due to eccentric-concentric work of muscle with dissimilar character and purpose in both phases. Earlier reports have demonstrated that the values of leg stiffness in the countermovement and take-off phases during CMJ should be similar [24]. Movement patterns for both limbs during countermovement and take-off phases in CMJ are similar. Therefore, the question can be asked whether stiffness will be similar in left and right lower limb.

## 2. Material and methods

The study was conducted among 35 basketball players from II division. The study group was characterized by the following mean parameters ( $\pm$ SD): body height – 190.4  $\pm$  8.1 cm, body mass – 81.9  $\pm$  10 kg, age – 19.5  $\pm$  1.7 years. Training experience was 6.8  $\pm$  2.5 years. A dominant limb used by each athlete to shoot the ball during a game was the right one. During all measurements, the study participants were wearing professional basketball shoes they wear during everyday training. The tests were carried out in the Biomechanical Analysis Laboratory at the University School of Physical Education in Wrocław, Poland, with the quality management system certificate (ISO 9001:2009). Prior to the tests, the participants were familiarized with the purpose of the study and signed their written consent for participation in the experiment. Before the experiment, the subjects were informed about the activities they were supposed to perform and were motivated to properly perform the assignment. The research project was approved by the Senate's Research Bioethics Commission at the University School of Physical Education in Wrocław, Poland.

Ground reaction forces were measured using two Kistler force plates (9286A) in order to ensure measurement of the ground reaction forces for each limb separately. The time of take-off and landing allows for evaluation of the duration of the flying phase and, consequently, calculate the jump height. The kinematic data were recorded by BTS SMART system

(BTS Bioengineering, Milan, Italy) for comprehensive motion analysis based on technology of passive markers that reflect infrared radiation (IR). The system features 6 cameras with frame rate of 120 Hz. In order to facilitate synchronization of the measurements, the sampling rate for the signal from force plates was set at 240 Hz. BTS SMART Analyzer software aids synchronization of the data recorded and preparation of a report from measurements.

Before the test, all study participants underwent an individual warm-up procedure which consisted of continuous shuttle run over the distance of 10 m. The run occurred at a moderate pace of ca. 10 distances per minute and was continued until reaching the heart rate of 150 bpm. The reflection markers were located at the height of the greater trochanters of the femur. During the measurement of body weight, the participants stood on the plates (each feet on separate plate) and maintained body motionless for 5 seconds. Additionally,  $L$  variable, which was the height of the markers located at the greater trochanters of the femurs (used as a conventional upper end of lower limbs) was also measured. It was adopted that the change in the height of the greater trochanter represents a measure of the change in the "length" ( $\Delta l$ ) of virtual spring (which represents lower limb). The measurement of  $\Delta l$  strain performed in this manner represents lower limb strain more accurately than the change in the height of the centre of mass for the whole body, with its displacement depending on changes in locations of all the body parts. The next step was to record three CMJ for maximum height. Upon a signal, the athlete performed a vertical jump, preceded by a rapid countermovement of lower limbs and arm swing. Landing was performed on the same platforms as take-off. The focus was also on simultaneous take-off from both lower limbs. A 10-second rest took place before single jumps. The analysis concerned the highest jump performed by each participant. Figure 1 presents an analogy between human movement (during performance of lower limbs countermovement) and a simple spring-mass model.

Leg stiffness was determined as a ratio of changes in ground reaction forces to the respective changes in the height of the greater trochanter of the femur (recorded by BTS Smart system based on marker displacements). Countermovement is understood as lowering the position (through flexing lower limbs), followed by immediate take-off. Therefore, the countermovement phase starts at the moment of a decline of the ground reaction force curve with respect to the value equal to body weight and ends at maximum knee joint flexion (maximum greater femoral tro-

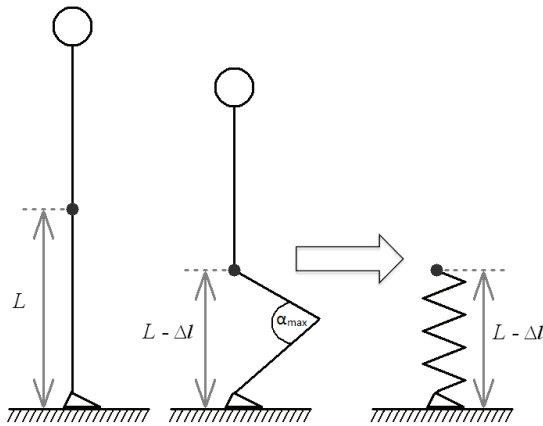


Fig. 1. Motion pattern of human body and spring-mass model during counter movement, where  $L$  denotes lower limb length,  $\Delta l$  is lower limb strain and  $\alpha_{\max}$  is the value of knee joint angle that determines the boundary between the phases of counter movement and take-off

chanter displacement). The end of the countermovement phase is also the beginning of the take-off phase, which ends at the moment when the feet losing contact with the ground (value of ground reaction forces drops to zero) and beginning of the flying phase. Leg stiffness was calculated in the parts of the countermovement phase and take-off phase where slope of the  $F$  curve with respect to the  $\Delta l$  axis was relatively constant and the  $F(\Delta l)$  profile was nearly linear (Fig. 2). It is only these parts that allow for expression of leg stiffness by means of a (single) concrete numerical value. For the countermovement phase, this was the part between the lowest value of ground reaction force and the lowest position of the greater trochanters of the femurs (marked dark grey in Fig. 2). The boundaries of the part for the take-off phase were represented by local maximum of ground reaction forces (points from which ground reaction forces only decreased) and the moment of take-off from the plates (marked light grey in Fig. 2) [24]. Therefore, this calculation was approximate in the above parts of the  $F(\Delta l)$  curve slope, with its slope coefficient equal numerically to stiffness.

The initial part of the take-off phase (dotted part of the  $F(\Delta l)$  curve presented in Fig. 2) was disregarded in the analysis due to the difficulty of its unequivocal interpretation. The profile of the  $F(\Delta l)$  curve in this part is unique and shows strong interindividual variability and the variability between individual repetitions of the jump.

The relative leg stiffness was obtained through normalization of the absolute value with respect to body mass. The legitimacy of this procedure can be explained with the effect of inertia on final leg stiffness value [11], [17], [24].

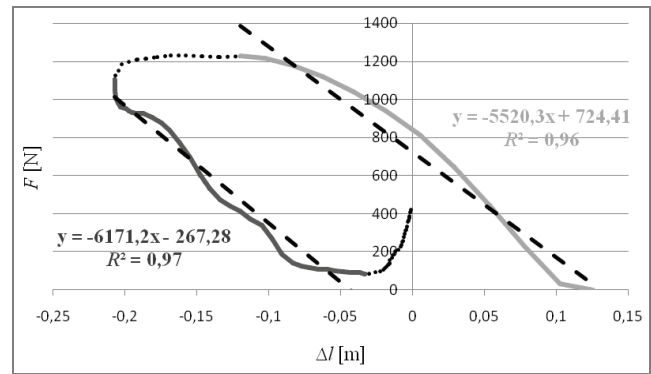


Fig. 2. Ground reaction force in left lower limb for one of the study participants depending on vertical displacement of the greater trochanter of the femur with respect to the ground with trend lines for the parts studied and values of determination coefficient  $R^2$  that represent the quality of model match (trend line to parts of profiles of the  $F(\Delta l)$  curve)

Leg stiffness measurement error is composed of the measurement error for two values of vertical component of ground reaction forces and measurement error of two vertical coordinates of marker location. Measurement error for vertical component of ground reaction force measured using the Kistler force plate is composed of:

- error of sensitivity of conversion of the pressure force into electric charge,  $\delta_s = \pm(0.5 \div 1)\%$ ,
- error of linearity of conversion of the pressure force into electric charge,  $\delta_l = \pm(0.3 \div 0.5)\%$ ,
- error of hysteresis of conversion profile,  $\delta_H = \pm(0.3 \div 0.5)\%$ ,
- error of charge amplifier,  $\delta_a \leq \pm 1\%$ ,
- error of analog-to-digital converter, which contains the analog component  $\delta_k \leq \pm 0.5\%$  and quantization error which depends on the resolution of the converter,
- dynamic errors connected with frequency properties of the measurement track, (usually disregarded in error analyses due to difficulties with evaluation of these errors).

The errors caused by the above components of the measurement track are aggregated. Therefore, it can be adopted that the total relative error of measurement of the vertical component of ground reaction force by means of the Kistler force plate model used in the study is not greater than  $(2.6 \div 3.5)\%$ , assuming that the force measured has the value close to the upper limit of the measurement range. In another case, i.e., during measurement of the lower force, the error is higher, e.g., measurement of the force with the value corresponding to the half measurement range will show twice greater error i.e. in the range of  $(5.2 \div 7)\%$ . According to the documentation of BTS SMART

system, measurement of vertical coordinate of marker location occurs with relative error  $\Delta_y \leq \pm 0.85$  mm, thus the value of relative measurement error is lower than 1%. Therefore, error of measurement of leg stiffness is not greater than (7.2÷9)%.

The vertical component of the movement velocity of the conventional upper end of the lower limbs (represented by the vertical velocity of the markers) was calculated as a time derivative of marker displacements (markers located at the greater trochanters of the femurs).

Due to the normal distribution, analysis of the differences between the variables was based on the *t*-test for dependent variables. The level of significance was set at  $\alpha = 0.05$ . Advanced Statistica 10 PL software package was used for this purpose.

### 3. Results

Table 1 presents mean values ( $\pm$ SD) of leg stiffness in the countermovement and take-off phases of the CMJ. Statistical analysis found no significant differences between leg stiffness in the countermovement and take-off phases in the group studied ( $p > 0.05$ ). No statistically significant differences were found during comparison of stiffness in the right and left lower limb. Mean height of CMJ used for analysis was  $0.45 \pm 0.05$  m.

lower limb should be one-dimensional and the measurements should be performed in steady states of body strain (equilibrium). The overall form of the simplified linear equation of one-dimensional motion of the system including mass, damping component and spring is given by

$$F = m \cdot a + b \cdot v + K \cdot l \quad (3)$$

where  $F$  denotes the force,  $m$  – mass,  $a$  – acceleration,  $b$  – damping,  $v$  – velocity,  $K$  – stiffness and  $l$  – length. Therefore, in formal terms, length derivative of force represents not only stiffness, but also a complex expression which also contains the factors responsible for damping and inertia. The above derivative depends not only on changes in  $m$ ,  $b$  and  $K$  over time but also on motion kinematics. If measurement of stiffness is not performed in steady states of body strain, the substantial value of  $dF/dl$  might contain the components originating from inertia forces and damping [17]. Application of equation (3), despite its simplified form, is practically impossible, at least due to the impossibility of determination of the value of damping in the area of lower limbs. Additionally, the conceptual and methodological confusion connected with the concept of stiffness seems to be insignificant compared to the confusion related with the concept of “damping” and “viscosity”. Zatsiorsky [26] found eleven different interpretations of the concept of “viscosity”. Equation (1) was obtained through simplification. Therefore, the stiffness of components of the motion system in

Table 1. Mean values ( $\pm$ SD) of leg stiffness in the phases of CMJ

	$K$ (kN/m)		
	Left lower limb ( $K_L$ )	Right lower limb ( $K_L$ )	Total ( $K_L + K_R$ ):
Countermovement phase	$3.6 \pm 1.2$	$3.5 \pm 1.2$	$7.1 \pm 2.3$
Take-off phase	$3.8 \pm 0.6$	$3.7 \pm 0.5$	$7.5 \pm 1$
	$K_{rel}$ (kN/(m·kg))		
Countermovement phase	$0.044 \pm 0.015$	$0.043 \pm 0.016$	$0.087 \pm 0.029$
Take-off phase	$0.046 \pm 0.005$	$0.046 \pm 0.006$	$0.092 \pm 0.011$

$K$  denotes absolute leg stiffness, whereas  $K_{rel}$  is relative leg stiffness.

### 4. Discussion

The construction of the living motion system causes that, from the formal standpoint, dynamic analysis has to take into consideration the components that cause inertia forces and damping in a model of human body. Additionally, the spring that represents

human body obtained from this equation does not meet the criteria of formal accuracy and, consequently, is subject to error. Therefore, the leg stiffness is not the stiffness viewed in strict terms due to a substantial contribution of other factors that have an effect on the  $F(\Delta l)$  relationships, especially during transient states. According to the division of Latash and Zatsiorsky [17], stiffness calculated from equation (1)

that stems from mechanics should, with respect to living bodies, be termed quasi-stiffness ( $q$ ), given by

$$q = \frac{\Delta F}{\Delta l}. \quad (4)$$

Latash and Zatsiorsky [17] defined quasi-stiffness as an ability of human body to oppose to the external displacements with disregard to the profile of displacements with respect to time. Therefore, in the studies concerning human motion, one should use the above concept. Numeral value of quasi-stiffness (equation (4)) seems to be elevated compared to actual stiffness (equation (3)). In our article to avoid excessive chaos compared to the commonly used expressions, leg quasi-stiffness is termed leg stiffness and denoted with  $K$  symbol. There are a number of “varieties” of stiffness, including: *musculoskeletal*-, *musculotendinous*-, *musculoarticular*-, *dynamic*-, *joint*-, (*intrinsic*) *muscle*-, *short range*-, *vertical*-, *limb*-, *total body* -stiffness. Therefore, it should be noted that the term stiffness is used to denote the variables which do not match its strict definition, which is additionally reflected by the use of units which are untypical of stiffness, such as Nm or  $s^{-2}$  [5], [14]. Therefore, the attempts to systematize the meaning of the term stiffness proposed by Latash and Zatsiorski [17], which ensures solving the problem of the conceptual chaos around stiffness seems to be critical. However, lack of direct use of the term quasi-stiffness seems to be the smallest yet common mistake that causes misinterpretations. The use of general displacement of the centre of mass as  $\Delta l$  causes that the value of leg stiffness is not calculated at all. The change in  $\Delta l$  occurs not in the lower limbs but in the whole body and depends on the spatial position of each body part, including upper limbs. In this case, one should use the concept of vertical stiffness that relates to the whole body rather than only to lower limbs [5], [7], [8], [14]. Therefore, the substantial majority of the studies on leg stiffness should be properly qualified as vertical quasi-stiffness of human body. Due to the above, this study seems to be one of the few studies that actually relate to leg quasi-stiffness.

The profile of the  $F(\Delta l)$ , which in the counter-movement phase (part between the lowest value of ground reaction force and the lowest position of the greater trochanters in the femurs of the subject) and the take-off phase (part between local maximum of ground reaction force from which the value of ground reaction force only decreased and the moment of take-off from the plates) of single CMJ is similar to linear, allowed for calculation of leg stiffness in parts of these phases (see Table 1). The charts analogous to

the chart presented in Fig. 2 have been previously obtained by various authors [3], [5], [7]–[12], [14], [21], [25]. However, estimation of stiffness based on these charts has not been often performed in practice. Probably the first researchers that are likely to have determined the relative value of vertical stiffness in humans in motion (running) were Cavagna et al. [5]. For this purpose, they used the profile of changes in the vertical component of acceleration of the centre of mass as a function of changes in its displacement. The slope of the curve determined during the foot contact with the ground was estimated using the least square method. Arampatzis et al. [2] attempted to use the analogous method to determine leg stiffness during the amortization phase of drop jump (DJ), obtaining the linear profile of changes in ground reaction forces to displace of COM. Furthermore, Granata et al. [11] verified linearity of the  $F(\Delta l)$  curve for hopping by correlating the vertical ground reaction force with COM displacement. If the value of correlation coefficient  $r$  exceeded 0.8, the profile was considered as linear. Presently, the method based on linear regression was displaced by the faster and simpler method, which requires only the use of force plate. The value of leg stiffness ( $K$ ) is mostly calculated based on the equation in the form

$$K = \frac{F_{\max}}{\Delta l}, \quad (5)$$

or

$$K = \frac{F_{\max}}{\Delta l_{\max}}, \quad (6)$$

where  $F_{\max}$  denotes maximal ground reaction force,  $\Delta l$  is lower limbw strain understood as COM displacement, and  $\Delta l_{\max}$  means maximum displacement of the COM during contact with the ground. For such cyclic movement as running or hopping, the above procedures require several assumptions that many authors seem to neglect, whereas measurement reliability would require their verification. Firstly, maximal value of ground reaction force must occur exactly at the same time as extreme position of the COM. Then, the increment in ground reaction force with respect to COM displacement is linear or close to linear over the whole duration of the phase of contact with the ground. Therefore, the moment of reaching the  $F_{\max}$  value should additionally divide contact time into two halves (harmonic motion). Theoretically, this ensures the same values of stiffness during the amortization (deceleration) and take-off phases and justifies the use of a single value (neglecting computations for the take-off phase) as the leg stiffness during a specific

motion. It seems that these assumptions for hopping (with frequency higher than 2 Hz) should be reflected in reality (at least in the most of the cases) which is consistent with the charts obtained by Ferris and Farley [10], Farley et al. [9], Granata et al. [11] and Rabita et al. [21]. As shown by the curves  $F$  with respect to  $\Delta l$  axis presented by Farley and González [8], these conditions will not always be met, particularly for the run at a high velocity or with small stride frequency. For the hopping frequency lower than 2 Hz, lower limbs also stop acting as linear springs, which distorts  $F(\Delta l)$  profile [3], [7], [12]. Kuitunen et al. [16] demonstrated the simultaneous lack of maximum ground reaction force with extreme displacement of COM during hopping and single DJ. However, these authors neglected this fact during calculations. The linear profile of  $F(\Delta l)$  during running is disturbed by strong heel strike [14]. Therefore, it is necessary, as it is the case in this study, to determine leg stiffness for both phases of movement separately. Assumption that the value of leg stiffness in the amortization (deceleration) phase is the same as in the take-off phase without verification of this thesis is too big simplification. One solution was suggested by Hunter [14], who proposed separation of the heel strike from the support phase of running as a part with much greater stiffness compared to other parts of gait cycle. The above requirements cause that the use of equations (5) and (6) is little rational (still possible) for the CMJ, and similarly problematic for DJ as in the case of running. By analogy, the calculation methodology presented in our study can be successfully used for calculation of stiffness during other movements, including commonly examined motions such as walking, running or jumping.

The rough values of leg stiffness during locomotion movements which can be found in the literature vary substantially. Ranges of leg stiffness are 2–8 kN/m [24], [25], 5–95 kN/m [2], [16] and 8–75 kN/m [6], [7], [9]–[11], [13], [19], [21], [23] during CMJ, DJ and hopping, respectively. Substantial variability in leg stiffness might result from the use of various research methodologies (for measurements and calculations) which are not always used adequately from the formal standpoint. This prevents from comparison of the results obtained by other authors and causes a methodological and conceptual ambiguity concerning what stiffness actually means and how it should be examined. Therefore, it is important for these studies to describe the methodologies used in detail so that it can be unequivocally verified whether the value studied is actual stiffness. Undoubtedly, substantially higher values of leg stiffness com-

pared to the results obtained in our study might result from calculations which were inconsistent with the profile of the  $F(\Delta l)$  curve. This is caused by the use of  $\Delta F$  and  $\Delta l$  (often extreme) for which changes (maximal in the case of extreme values) do not correspond to each other. This usually causes overestimation of leg stiffness value. It is essential during evaluation of limb stiffness to create the chart for the relationship  $F(\Delta l)$  (as in Fig. 2). Slope coefficient for the part of curve analysed equals numerical value of stiffness in this part. Figures 3 and 4 illustrate how application of equations (5) and (6) for single CMJ affects leg stiffness and disturbs the shape of instantaneous profile of the  $F(\Delta l)$  curve. Therefore, leg stiffness examined in this study differs from this value determined based on equations (5) and (6).

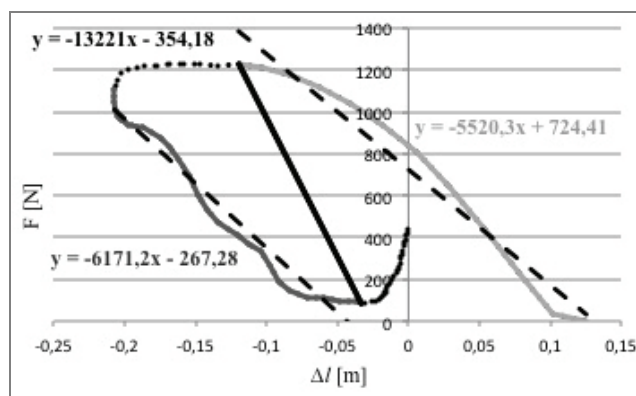


Fig. 3. Slope coefficient for the  $F(\Delta l)$  curve for parts of the counter-movement phase (ca. 6170 N/m), take-off (ca. 5520 N/m) and calculated based on equation (5) (ca. 13200 N/m)

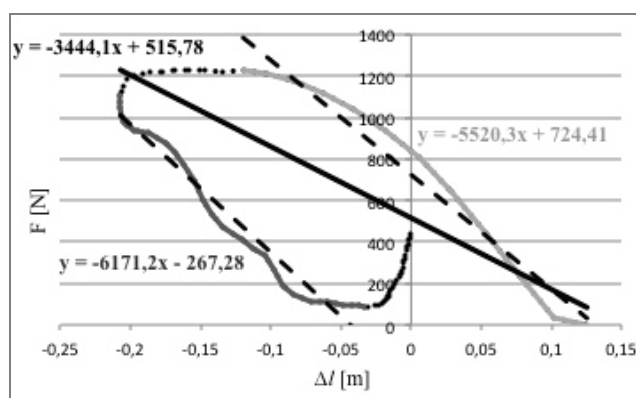


Fig. 4. Slope coefficient for the  $F(\Delta l)$  curve for parts of the counter-movement phase (ca. 6170 N/m), take-off (ca. 5520 N/m) and calculated based on equation (6) (ca. 3440 N/m)

As expected, leg stiffness for single CMJ was relatively constant [24]. No statistically significant

differences were found in the value of stiffness in the countermovement and take-off phases. This leads to the conclusion that the values of the variables studied are much similar to each other despite different tasks performed in individual phases. This is likely to be attributable to the velocity and duration of the movement. During running or hopping, leg stiffness maintains a relatively constant level if the frequency of the movement is not changed [3], [5], [8], [10]–[12], [16]. Figure 5 shows that the profile of ground reaction forces with respect to movement velocity in the parts of the countermovement and take-off phases is relatively linear, similar to  $F(\Delta l)$  and is additionally characterized by extremely substantial slope. Therefore, leg stiffness during a single vertical jump maintains a relatively constant value over the parts with low value of acceleration (relatively constant motion velocity).

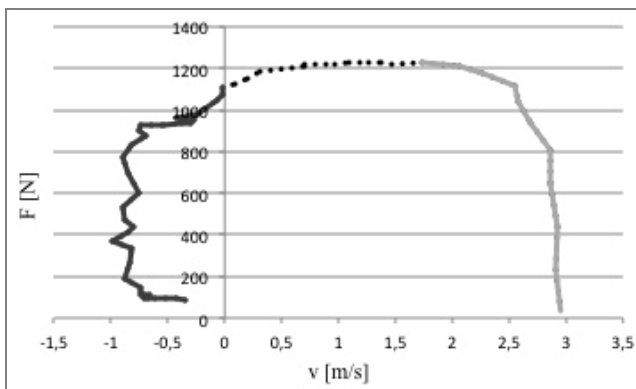


Fig. 5. Ground reaction force for the left lower limb in one of the study participants with respect to vertical component of velocity of the greater trochanter of the femur with marked parts for the countermovement and take-off phases, by analogy to Fig. 2

An uneven growth of the core muscles in basketball players is caused by performing the activities connected with the specific nature of the sport and the habitual use of the dominant body parts. Lack of equal distribution of training load leads to substantial functional asymmetry and the asymmetry in muscle force distribution, mainly in the area of lower limb. This phenomenon is unfavourable and is conducive to injuries [22]. Therefore, the lack of statistically significant differences between the right and left lower limb stiffness should be regarded as a positive phenomenon. Pruyn et al. [20] and Hobara et al. [12] determined the level of differences in leg stiffness during unilateral hopping. The undesired state was the value of difference which exceeds 7% and 10%.

## 5. Conclusions

1. Leg stiffness examined by the authors should be termed leg “quasi-stiffness”, similarly to other studies that have examined human continuous motion due to the contribution of inertia and damping to the final result. The calculation methodology presented in this study allows for estimation of the value of leg stiffness based on the actual profile of the  $F(\Delta l)$  curve rather than on the extreme values of  $\Delta F$  and  $\Delta l$ .
2. Leg stiffness during a single, maximum CMJ is lower compared to the values that can be found in the literature (mainly during cyclic motion such as running, walking and hopping). Substantially higher values of leg stiffness compared to the results obtained in this study might result from calculations which were inconsistent with the profile of the  $F(\Delta l)$  curve.
3. No statistically significant differences were found between leg stiffness in the countermovement and take-off phases in the group studied. Despite different tasks of the phases studied, level of stiffness during these phases is much similar. Therefore, the value of leg stiffness during a single, maximum CMJ turned out to be relatively constant.
4. Leg stiffness during a single vertical jump maintains a relatively constant value over the parts with low value of acceleration (relatively constant motion velocity).
5. No statistically significant differences were found during comparison of stiffness in the right and left lower limb. Therefore, stiffness values for the right and left lower limb during CMJ are much similar to each other.

## References

- [1] ANDERSON F.C., PANDY M.G., *Storage and utilization of elastic strain energy during jumping*, J. Biomech, 1993, Vol. 26(12), 1413–1427.
- [2] ARAMPATZIS A., SCHADE F., WALSH M., BRÜGGEMANN G.-P., *Influence of leg stiffness and its effect on myodynamic jumping performance*, J. Electromyogr. Kines., 2001, Vol. 11(5), 355–364.
- [3] BLUM Y., LIPPERT S.W., SEYFARTH A., *Effective leg stiffness in running*, J. Biomech., 2009, Vol. 42(14), 2400–2405.
- [4] BRUGHELLI M., CRONIN J., *A review of research on the mechanical stiffness in running and jumping: methodology and implications*, Scand. J. Med. Sci. Spor., 2008, Vol. 18(4), 417–426.
- [5] CAVAGNA G.A., FRANZETTI P., HEGLUND N.C., WILLEMS P., *The determinants of the step frequency in running, trotting and hopping in man and other vertebrates*, J. Physiol., 1988, Vol. 399(1), 81–92.



- [6] DALLEAU G., BELLI A., VIALE F., LACOUR J.-R., BOURDIN M., *A simple method for field measurements of leg stiffness in hopping*, Int. J. Sports Med., 2004, Vol. 3(25), 170–176.
- [7] FARLEY C.T., BLICKHAN R., SAITO J., TAYLOR C.R., *Hopping frequency in humans: a test of how springs set frequency in bouncing gaits*, J. Appl. Physiol., 1991, Vol. 71(6), 2127–2132.
- [8] FARLEY C.T., GONZÁLEZ O., *Leg stiffness and stride frequency in human running*, J. Biomech., 1996, Vol. 29(2), 181–186.
- [9] FARLEY C.T., HOUDIJK H.H.P., VAN STRIEN C., LOUIE M., *Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses*, J. Appl. Physiol., 1998, Vol. 85(3), 1044–1055.
- [10] FERRIS D.P., FARLEY C.T., *Interaction of leg stiffness and surface stiffness during human hopping*, J. Appl. Physiol., 1997, Vol. 82(1), 15–22.
- [11] GRANATA K.P., PADUA D.A., WILSON S.E., *Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks*, J. Electromyogr. Kines., 2002, Vol. 12(1), 127–135.
- [12] HOBARA H., INOUE K., KANOSUE K., *Effect of hopping frequency on bilateral differences in leg stiffness*, J. Appl. Biomech., 2013, Vol. 29(1), 55–60.
- [13] HOBARA H., INOUE K., KOBAYASHI Y., OGATA T., *A comparison of computation methods for leg stiffness during hopping*, J. Appl. Biomech., 2014, Vol. 30(1), 154–159.
- [14] HUNTER I., *A new approach to modeling vertical stiffness in heel-toe distance runners*, J. Sport Sci. Med., 2003, Vol. 2(4), 139–143.
- [15] KOMI P.V., GOLLHOFER A., *Stretch reflexes can have an important role in force enhancement during SSC exercise*, J. Appl. Biomech., 1997, Vol. 13(4), 451–459.
- [16] KUITUNEN S., KYRÖLÄINEN H., AVELA J., KOMI P.V., *Leg stiffness modulation during exhaustive stretch-shortening cycle exercise*, Scand. J. Med. Sci. Spor., 2007, Vol. 17(1), 67–75.
- [17] LATASH M.L., ZATSIORSKY V.M., *Joint stiffness: myth or reality?* Hum. Movement Sci., 1993, Vol. 12(6), 653–692.
- [18] MORAN K.A., WALLACE E.S., *Eccentric loading and range of knee joint motion effects on performance enhancement in vertical jumping*, Hum. Movement Sci., 2007, Vol. 26(6), 824–840.
- [19] MRDAKOVIC V., ILIC D., VULOVIC R., MATIC M., JANKOVIC N., FILIPOVIC N., *Leg stiffness adjustment during hopping at different intensities and frequencies*, Acta Bioeng. Biomech., 2014, Vol. 16(3), 69–76.
- [20] PRUYN E.C., WATSFORD M.L., MURPHY A.J., PINE M.J., SPURRS R.W., CAMERON M.L., JOHNSTON R.J., *Relationship between leg stiffness and lower body injuries in professional Australian football*, J. Sport Sci., 2012, Vol. 30(1), 71–78.
- [21] RABITA G., COUTURIER A., LAMBERTZ D., *Influence of training background on the relationships between plantar-flexor intrinsic stiffness and overall musculoskeletal stiffness during hopping*, Eur. J. Appl. Physiol., 2008, Vol. 103(2), 163–171.
- [22] SCHILTZ M., LEHANCE C., MAQUET D., BURY T., CRIELAARD J.-M., CROISIER J.-L., *Explosive strength imbalances in professional basketball players*, J. Athl. Training, 2009, Vol. 44(1), 39–47.
- [23] SERPELL B.G., BALL N.B., SCARVELL J.M., SMITH P.N., *A review of models of vertical, leg, and knee stiffness in adults for running, jumping or hopping tasks*, J. Sport Sci., 2012, Vol. 30(13), 1347–1363.
- [24] STRUZIK A., ZAWADZKI J., *Leg stiffness during phases of countermovement and take-off in vertical jump*, Acta Bioeng. Biomech., 2013, Vol. 15(2), 113–118.
- [25] WANG L.-I. *The kinetics and stiffness characteristics of the lower extremity in older adults during vertical jumping*, J. Sport Sci. Med., 2008, Vol. 7(3), 379–386.
- [26] ZATSIORSKY V.M., *On muscle and joint viscosity*, Motor Control, 1997, Vol. 1(4), 299–309.
- [27] ZAWADZKI J., *Cyclic movements as a form of mechanical resonance in the human musculoskeletal system*, [in:] T. Bober, A. Siemieński (eds.) *Contemporary biomechanics: selected topics*, International Congress of the Polish Society of Biomechanics “Biomechanics ’08” Wrocław, Wydawnictwo AWF, Wrocław, 2008, 66–79.
- [28] ZAWADZKI J., SIEMIEŃSKI A., *Maximal frequency, amplitude, kinetic energy and elbow joint stiffness in cyclic movements*, Acta Bioeng. Biomech., 2010, Vol. 12(2), 55–64.