Leg stiffness during phases of countermovement and take-off in vertical jump

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With respect to cyclic movements such as human gait, running or hopping, leg stiffness is a little variable parameter. The aim of this study was to investigate changes in leg stiffness during the phase of countermovement and take-off when performing a single maximum counter-movement jump. Kistler force plates and a BTS SMART system for comprehensive motion analysis were employed in the study. The study covered a group of 12 athletes from university basketball teams. Leg stiffness was calculated in those parts of counter-movement and take-off phases where its level is relatively constant and the relationship $F(\Delta l)$ is similar to linear one. Mean total stiffness (±SD) in both legs in the countermovement phase amounted to 6.5 ± 1.5 kN/m, whereas during the take-off phase this value was 6.9 ± 1 kN/m. No statistically significant differences were found between leg stiffness during the countermovement phase and take-off phase in the study group at the level of significance set at $\alpha = 0.05$. This suggests that the leg stiffness in phase of countermovement and phase of take-off are much similar to each other, despite different function of both phases. Similar to cyclic movements, leg stiffness turned out relatively constant when performing a single vertical jump. There are also reported statistically significant correlations between body mass, body height, length of lower limbs and leg stiffness. The stiffness analysed by the authors should be understood as quasi-stiffness because the measurements of $\Delta F(\Delta l)$ were made during transient states where inertia and dumping forces are likely to affect the final result.

Key words: basketball players, counter-movement jump, quasi-stiffness

1. Introduction

Counter-movement jump (CMJ) is a complex movement which involves both lower and upper extremities. The absolute measure of CMJ effectiveness is provided by the height of jump. Elastic energy, stretch-shortening cycle (SSC), muscle contraction rate (excitation of motor units) and its power are factors which have direct effect on final velocity at the take-off and are critical to jumping height. Depending on the type of jump, it is necessary to find a trade-off between the range and velocity at the take–off, which would consequently lead to the determination of perfect movement patterns. When performing a counter-movement (lower limbs flexion) before the take-off, an athlete induces a rapid stretch in the muscles before the contraction, which causes that more work is done by the muscles in concentric phase and consequently higher impulse is generated at the take-off. If this work is done within a shorter time, the power will increase accordingly. The contributing factor to the increased work is the phenomenon of tissue elasticity which manifests itself in the stretch–shortening cycle and stretch reflex. The capacity of tendinomuscular systems to store and use potential elasticity energy magnifies the contraction even more [1], [2].

When exposed to the stretching force, a muscle changes its length (e.g., it is elongated during the eccentric phase). The change will be maintained as long as the force is applied. When the force is removed, the muscle returns to the primary state and, if this means a resting state, it reaches the length of l_0. As this change in the length is not permanent, it can be re-

garded as elastic strain. Elasticity is a property of macroscopic bodies which consists in the ability to return to its original shape and volume after the mechanical forces cease to act (the changes are fully recoverable). The quantitative measure of elastic properties of solids is their stiffness, which represents a measure of resistance to deformation (compliance is the opposite of stiffness). Stiffness is the ratio of the value of the deformation cause (force, moment of force) to the quantitative measure of the deformation. The formula (1) presents the stiffness with respect to linear deformations, whereas formula (2) concerns angular deformations [2]. Dividends in equations are the causes of changes in deformation (ΔF – forces, ΔM – moment of force), whereas divisors are the values of deformation (Δl – linear, $\Delta \alpha$ – angular).

$$K_l = \frac{\Delta F}{\Delta l}, \tag{1}$$

$$K_\alpha = \frac{\Delta M}{\Delta \alpha}. \tag{2}$$

In order to return to its initial state, a spring elongated by an increment Δl with a force ΔF will produce the force with the same magnitude but the opposite direction ($-\Delta F$). There is a proportional relationship for linear spring between the value of force ΔF and the deformation it caused Δl. However, human muscles do not work as linear springs. Muscle contractions cause an increase in muscular stiffness and ability to accumulate elastic energy, whereas relaxing the muscle increases the susceptibility to deformations. Therefore, it cannot be assumed that the relationship $\Delta F/\Delta l$ in muscles is linear as it is the case in ideal spring [2]–[4].

A number of studies have examined the leg stiffness during gait, running [5]–[7] or hopping [8]–[11]. However, few studies have analysed this problem with respect to a single maximum vertical jump [12], [13]. Gender [10], age [13] and body mass of an individual affect the leg stiffness significantly, whereas the velocity of the movement performed contributes only to a minimum extent [5]. This results in that the leg stiffness does not change considerably during gait or running if stride frequency [6] or hopping frequency remains constant within a particular series [11]. An increase in frequency causes the increase in leg stiffness. The majority of studies have focused on the structure of movements of cyclic nature, which are unlike the maximum vertical jump. The type of surface where a test is carried out is also essential. Lower stiffness of the surface will cause the increase in leg stiffness and its higher values [8], [9].

Jump is a complex movement, which is characterized by an eccentric–concentric muscle work during the phases of countermovement and take-off, with different character and functions of both phases. This might suggest different level of leg stiffness during the phase of countermovement and take-off. However, total duration of both phases (ca. 0.5 s) might be too short for significant changes to occur. Furthermore, previous reports on the leg stiffness suggest that stiffness is a little variable parameter. This concerns, however, cyclic movements rather than single ones. Therefore, the aim of the study was to verify how the parameter of leg stiffness changes during such movements as single maximal vertical jump. The particular focus in the present study was on the phases of countermovement and take-off, which are the main factors in the effectiveness of the jump. If leg stiffness turns out to be a relatively constant parameter, it will be possible to determine its numerical value.

2. Materials and methods

The examinations were carried out in a group of 12 basketball players (7 males and 5 females), members of basketball division at a sport club AZS AWF Wrocław, who scored leading places in Lower Silesia University League. The study group was characterized by the following mean values (±SD): body height: 182.4 ± 14 cm; body mass: 77.8 ± 29 kg; age: 21.3 ± 1.7 years. During the test, the subjects were wearing professional basketball shoes they used during everyday training. The tests were carried out in the Biomechanical Analysis Laboratory at the University School of Physical Education in Wrocław, Poland (Quality Management System Certificate: PN-EN 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 motivated to properly perform the assignment. The examinations were positively approved by the Senate's Research Bioethics Commission at the University School of Physical Education in Wrocław, Poland.

Two Kistler force platforms (model: 9286A) were used for the measurement of ground reaction forces, which allowed the authors to record the effect of the left and right limb separately. The accurate measurement of the take-off and landing time helps assess the duration of flight phase and consequently the jumping

height. The kinematic data were registered by a BTS SMART system for comprehensive motion analysis based on the technology of passive markers that reflected the emitted infrared radiation (IR). The system is composed of 6 cameras with frame rate of 120 Hz and the resolution of 0.2 mm. In order to synchronize the measurement, the sampling frequency of the platforms was set at 240 Hz. SMART Analyzer software allows for synchronization of the obtained data and preparation of a multimedia report from the examination, integrated with video record. Preparations for the examination necessitated creation of a body model of a subject, which was then sent to the BTS Tracker software in order to identify the markers. The underlying assumption for the model was that human body is a system of solids where lower extremities change their length in a pattern similar to springs (Fig. 1). The literature reports usually focus on the models without division of lower limbs into two separate units [7], [14].
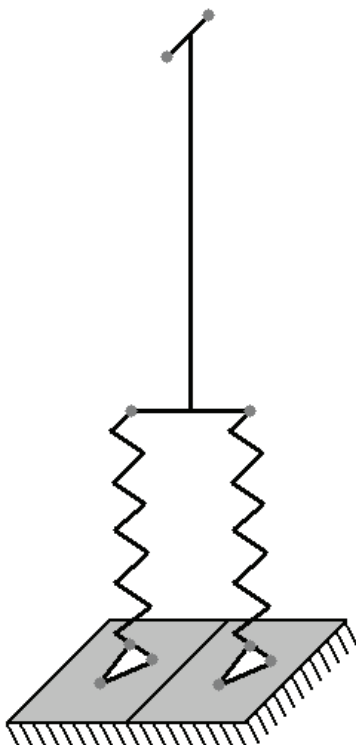

Fig. 1. A model of a subject examined

Prior to the examination, each subject warmed up for 10 minutes (continuous shuttle run). The purpose of this activity was to stimulate and warm up the muscles in order to make the best possible jump. Reflective markers were located at the height of the greater femoral trochanters. During the first measurement, subjects stood on force plates and remained motionless for 5 seconds. This was aimed at measuring body

weight and l_0 parameter, i.e., the height of the markers located on the greater femoral trochanters (conventional upper end of lower limbs). It was assumed that the measurement of deformation Δl will better reflect the character of changes in lower limbs compared to observation of the shift of body's centre of mass, which depends on location of all body parts. The next step was to record six CMJ jumps. The subjects stood on the platforms so that their limbs should be on different plates and performed, upon a signal, a jump, preceded by quick flexion of the knees and arm swing. The subjects were also asked to land on the same plates the jump was performed from. There was a several second rest between the jumps. It was also emphasized that the jump should be made from both legs simultaneously and the landing should be soft. The CMJ jump was chosen because it is the movement where a person is able to reach the maximum height and this jump is technically similar to the jumps made in basketball matches. It can also be used by coaches as a measure of jumping ability and control in plyometric sessions [15], [16]. The analysis focused on the three highest jumps made by each subject. The calculations were made in a Microsoft Excel spreadsheet. The differences in the values of leg stiffness during the phases of countermovement and take-off were analysed using a *t*-test for the significance of the differences for independent variables, with the level of significance set at $\alpha = 0.05$. The *r*-Pearson coefficient and *t*-Student test were applied to examine the correlation between the selected parameters. Statistica 10 PL advanced package was used for this purpose.

3. Results

Leg stiffness was determined as a ratio of changes in ground reaction forces to the respective changes in the height of the greater femoral trochanter. Figures 2 and 3 present ground reaction forces and changes in position of greater femoral trochanter vs. time during CMJ jump. The countermovement means lowering the positions (flexing lower limbs), followed immediately by jumping upwards. Therefore, the countermovement phase starts at the moment of a decline in the curve obtained for ground reaction forces with respect to the value of body weight and ends at maximum knee flexion. The end of the countermovement phase is also the beginning of the take-off phase, which ends at the moment when the feet leave the ground (the value of ground reaction forces drops to 0) and the flight phase starts.
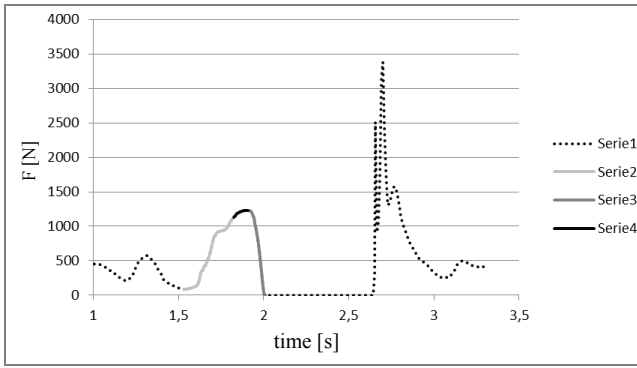
Fig. 2. Ground reaction forces in the left lower limb vs. time,
with investigated parts of phases of countermovement
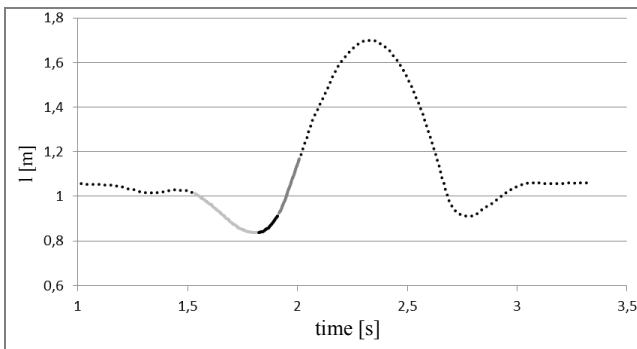(marked light grey) and take-off (marked dark grey)

Fig. 3. Height of the left greater femoral trochanter
with respect to the ground vs. time, with investigated parts
of phases of countermovement (marked light grey)
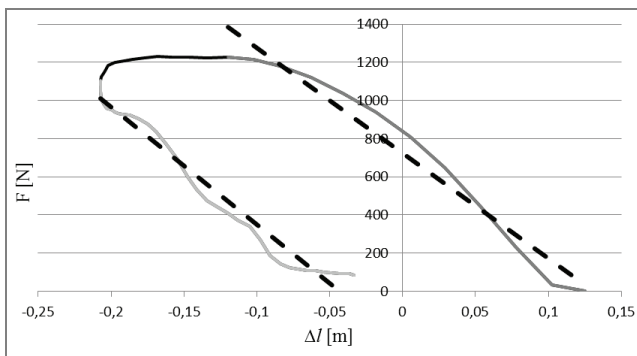and take-off (marked dark grey)

Fig. 4. Ground reaction forces in the left lower limb
in one of the subjects vs. vertical displacement
of the greater femoral trochanter with trend lines
for the intervals analysed

Leg stiffness $\left(K = \dfrac{\Delta F}{\Delta l} \right)$ was calculated only in the parts of countermovement and take-off where F curve slope with respect to the axis Δl is relatively constant (Fig. 4). In countermovement phase this was

a part between the lowest value of ground reaction force and the lowest position of greater femoral trochanter (marked light grey in Fig. 4). The borders of the part for the take-off phase were provided by local maximums of ground reaction forces (from which the value of ground reaction forces starts declining) and the moment of take-off from the plate (marked dark grey in Fig. 4).

Table 1. Mean values (±SD) for leg stiffness (K)
in countermovement and take-off phases of vertical jump

	K (kN/m)		
	Left lower limb (K_L)	Right lower limb (K_R)	Total ($K_L + K_R$)
Countermovement phase	3.39 ± 0.93	3.14 ± 0.79	6.5 ± 1.5
Take-off phase	3.5 ± 0.6	3.41 ± 0.54	6.9 ± 1

Table 1 presents mean values for leg stiffness (±SD) during the countermovement and take-off phases. Mean differences (±SD) between stiffness in these phases was 0.39 ± 1.17 kN/m, in favour of the take-off phase. No statistically significant differences were found between leg stiffness in the phases of countermovement and take-off in the study group with the level of significance set at $\alpha = 0.05$. This allowed the authors to conclude that the parameters studied are much similar to each other despite different functions of the phases. Table 2 presents mean values (±SD) of CMJ jump parameters obtained by the subjects.

Table 2. Mean values (±SD) of maximal take-off force ($F_{take-off}$),
maximal flexion angle in knee joint
during the countermovement phase (α), flight time (t_{flight})
and CMJ jump height (h_{jump}) for both lower limbs

	$F_{take-off}$ (N)	α (°)	t_{flight} (s)	h_{jump} (m)
Left lower limb	890 ± 190	78 ± 9.8	0.53 ± 0.08	0.36 ± 0.1
Right lower limb	847 ± 217	79 ± 9.4		

Table 3 presents values of correlations between somatic parameters and leg stiffness. The are reported very strong, positive, statistically significant correlations between body mass and leg stiffness; very strong, positive, statistically significant correlations between body height and leg stiffness, and strong, positive, statistically significant correlations between length of lower limbs and leg stiffness.

Table 3. Values of correlations between body mass (*m*),
body height (*h*), length of lower limbs (*l*) and leg stiffness (*K*)
during countermovement (CM P) and take-off (TO P) phases

	K					
	Left lower limb (K_L)		Right lower limb (K_R)		Total ($K_L + K_R$)	
	CM P	TO P	CM P	TO P	CM P	TO P
m	0.91*	0.92*	0.83*	0.97*	0.9*	0.96*
h	0.77*	0.68*	0.74*	0.76*	0.79*	0.73*
l	0.58*	0.48**	0.58*	0.54**	0.6*	0.52**

* Statistically significant for $p < 0.05$.
** Statistically significant for $p < 0.1$.

4. Discussion

Previous studies on leg stiffness in jumping have typically focused on ground reaction forces measured by dynamometric force plates and displacement of the centre of mass [5], [6], [8]–[11], [13].

Table 4. Approximate values of leg stiffness
for certain movements presented in the literature [5]–[13]

	Maximum jump	Gait (running)	Hopping
Range of stiffness (kN/m)	1–55	5–90	6–130

Table 4 shows approximate values of leg stiffness presented in the literature for cyclic movements and a single maximum jump [5]–[13]. The substantial spread in leg stiffness is a result of different research methods (used for measurement and calculations) which were not always used appropriately. This makes it impossible to compare the results obtained by various authors and causes methodological confusion as to what the stiffness actually is and how it should be measured. Hence, it is essential to provide accurate description of the methodologies in order to verify whether the measured variable is actual stiffness. Considerably higher values of leg stiffness compared to the results obtained in the present study result from the calculations which were inconsistent with the curve $\Delta F(\Delta l)$. This is caused by the use of ΔF and Δl (sometimes extreme ones), with the changes (in maximum cases) that did not correspond to each other. This causes factitious increase in the value of leg stiffness [5]–[13]. Therefore, it is critical for stiffness measurements that a chart for the relationship of $\Delta F(\Delta l)$ is created (as in Fig. 4). The slope at a par-

ticular point of the curve will represent the stiffness in this range.

Leg stiffness measured by the authors is not stiffness by its definition due to the effect of other factors (such as inertia and damping) on the relationship $\Delta F(\Delta l)$, particularly during transient states [17]. Latash and Zatsiorsky proposed the division of 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.

Consequently, the studies concerning stiffness measured during human movement should be included into the third group. Therefore, it is critical to provide the accurate description of the research methodology to allow for the determination of what is actually measured. This division seems to be a remedy for the conceptual confusion over stiffness as this word has been overused with respect to other properties of human body [18], [19].

Very strong, statistically significant relationship between leg stiffness and body mass can confirm the significant influence of inertial forces on the measured stiffness. The positive nature of the correlation may be due to the maintenance by the human body of its own natural frequency (*f*) determined by internal elastic forces and inertia. These findings confirm previous reports on relationships between body mass and leg stiffness during running [5]. The dependence of the natural frequency on the stiffness and body mass is shown by the following equation (3)

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}. \tag{3}$$

Similar to other types of movement (human gait, run, hopping), leg stiffness turned out to be a relatively little variable parameter [5]–[13]. For that reason, it can be concluded that the values of leg stiffness in the phases of countermovement and take-off are much similar to each other. Therefore, different functions and character of movement in both phases do not affect leg stiffness. This relationship allowed for numerical representation of leg stiffness in the measured ranges, which provides grounds for further research in this field.

5. Conclusions

1. Similar to leg stiffness during cyclic movements (such as human gait, running or hopping), leg stiffness during a single maximal counter-movement jump (CMJ) is a relatively little variable parameter.

2. Mean total stiffness (±SD) in both legs during countermovement phase was 6.5 ± 1.5 kN/m, whereas this value in take-off phase was 6.9 ± 1 kN/m.

3. No statistically significant differences were found between leg stiffness in the phases of counter-movement and take-off in the study group with the level of significance set at $\alpha = 0.05$. Despite different functions, stiffness remained similar throughout either of the phases.

4. The value of leg stiffness during a single maximal jump is lower compared to the leg stiffness in cyclic movements (human gait, running, hopping).

5. Higher values of body mass, body height or length of lower limbs were accompanied by higher values of leg stiffness. Leg stiffness is therefore person dependent. The positive relationship between body mass and leg stiffness may be due to the maintenance by the human body of its own natural frequency determined by internal elastic forces and inertia.

6. Stiffness measured by the authors should be viewed as quasi-stiffness, similar to all other studies that have examined humans during continuous movement, because inertia and dumping forces are likely to affect the final result.

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