Estimation of potential elastic energy
during the countermovement phase of a vertical jump
based on the force-displacement curve

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Purpose: One inconvenience in finding experimental evidence for the relationship between potential elastic energy and vertical jump height is the difficulty of estimating the value of the stored potential elastic energy. Therefore, the aim of this study is to present a simple method of estimating the potential elastic energy stored by lowering the center of mass during the countermovement phase of a vertical jump. *Methods*: The research was conducted on 30 able-bodied male university students (age: 20 years, body height: 183.1 ± 7.9 cm, body mass: 80.3 ± 10.4 kg). Each participant performed 10 single countermovement jumps with arms akimbo to maximal height. Measurements employed a Kistler force plate. The value of potential elastic energy was estimated based on the curve of dependence of the ground reaction force on the vertical displacement of the jumper's center of mass. *Results*: The mean value (±SD) of potential elastic energy collected due to lowering of the center of mass during the countermovement phase of a vertical jump was 183 ± 69 J. 24.3% of this value can be considered the part of the potential elastic energy (44 ± 21 J) that comes from the transformation of kinetic energy. The total change in gravitational potential energy due to lowering the center of mass was 240 ± 58 J. *Conclusions*: This estimation of potential elastic energy is only general and rough. However, certain estimations of potential elastic energy may offer some insight into the phenomenon relating vertical quasi-stiffness and the ability to store potential elastic energy with vertical jump height.

Key words: countermovement jump, elasticity, quasi-stiffness, stretch-shortening cycle

1. Introduction

Legged mammals move by using cyclic movements of the lower limbs. Consequently, the movement of the general center of mass (COM) is subject to alternate phases of acceleration and deceleration, which somewhat resembles a bouncing ball. Therefore, the term *"bouncing gait"* has been used to describe locomotion (i.e., walking, running, jumping, trotting or galloping) during which the lower limbs perform the role of "springs" (as in a pogo stick) responsible for COM movement. During these bouncing gaits, the actions of the body's musculoskeletal components (i.e., muscles, tendons, and ligaments) are integrated together so that the overall musculoskeletal

system behaves like a single spring. Therefore, the abovementioned methods of locomotion can be modeled by using simple spring-mass model that contains a single (linear and massless) *"leg spring"* and a point that represents the total body mass. The mechanical properties of a spring representing the lower limbs (i.e., stiffness) influence the mechanics and kinematics of the interaction with the ground [6], [7], [8].

Elasticity is a property of macroscopic bodies that consists of ability to recover the previous shape and volume after mechanical forces that cause deformation are removed. The quantitative measure of body elastic properties is stiffness, which represents the measure of resistance to strain. For an idealized spring with linear characteristics, there is a proportional relationship between the value of the force and the deformation re-

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sulting from Hooke's law. In this case, the work performed by the deformation forces equals the value of the potential elastic energy accumulated in the spring (assuming there are no energy losses due to friction and resistance forces). Deformed spring elements store the potential elastic energy, which they release when returning to the original length. The ability to absorb and recover elastic energy is also observed in tendinomuscular groups in the human body. A human muscle (as a whole), however, does not behave like an idealized spring with linear characteristics. A muscle is made of force-producing active (contractile) components and passive components (serial and parallel elastic elements) consisting of tendons, fascia and other connective tissues. The elastic properties and the ability to accumulate potential elastic energy of the above elements are different. Therefore, it cannot be stated that the dependence of force on the change in length is linear for muscles, as is the case of an idealized spring. The value of the force released by the muscle depends on the length of the muscle and the use of elastic elements, which increase the effect of contractile elements. If eccentric muscle activity (the excited muscle is extended due to external forces) and concentric muscle activity (the muscle length is reduced while overcoming external resistance) occur immediately after each other, the movement sequence is termed the stretch-shortening cycle (SSC). The eccentric-concentric action of muscles is conducive to the accumulation of potential elastic energy during cyclic and acyclic locomotor movements, including single vertical jumps. It has been argued that the efficiency of the SSC depends on the ability to transfer energy from the preactivated and eccentrically stretched muscle-tendon complex to the concentric push-off phase [13], [21], [24].

For a vertical jump to be performed, it is necessary that the central nervous system send electrical impulses to the muscles responsible for the movement. Consequently, electrical activity is increased in the excited muscles, activating processes that cause the conversion of chemical energy (obtained from food) into heat and mechanical energy (in the form of work done by the muscles). The total mechanical energy involved in human body movement is the sum of kinetic and potential energy. The kinetic energy associated with the movement depends on the inertia of the moving structure and velocity of the movement. Potential energy can occur as internal elastic energy and the potential energy of the gravitational field, which occurs in movements involving gravitational forces, e.g., during the majority of locomotor movements. The use of potential elastic energy allows for a reduction in the energy expenditure of muscles responsible for a move-

ment in a specific joint associated with the need for a change in the kinetic energy of the structure being moved. The potential energy of gravity is equal to the work that needs to be done to move the body between points with different heights [18], [21], [22].

During a vertical jump, the values of the kinetic energy, potential energy of gravity and potential elastic energy of the deformed tissue change. Potential elastic energy is defined as the energy of an elastically deformed body. A vertical jump performed with countermovement is an example of a movement based on the SSC. Therefore, it can be concluded that these deformations occur in the lower limb of a person who performs a vertical jump. Countermovement before the take-off in a vertical jump causes a rapid stretch of the extensors of the lower limb. Changes in the gravitational potential energy of COM during the countermovement phase cause the accumulation of potential elastic energy in the compliant tissues. The potential elastic energy accumulated during the countermovement phase increases the energy supplied by active contraction of the muscles used in the take-off phase. Consequently, the total mechanical energy used during the jump can be increased by the previously accumulated potential elastic energy. Transformation of the total mechanical energy during the flying phase into the potential energy of gravity allows a higher jump height to be obtained. Consequently, the potential elastic energy will impact the jump height [15], [20]. The occurrence of this phenomenon is considered to be one of the reasons for reaching mostly greater heights during a CMJ (countermovement jump, a vertical jump preceded by lower limb countermovement) than during a SJ (squat jump, vertical jump from a specific static position, i.e., a squat) [1], [5], [16].

One inconvenience in finding experimental evidence for the relationship between potential elastic energy and vertical jump height is the difficulty with estimating the value of stored potential elastic energy. The potential energy of gravity can be considered relatively easy to measure and can therefore be isolated in a closed form of energy balance. However, this does not make it easier to measure or estimate the contribution of potential elastic energy. This is caused by the unclear effect of the stiffness of pliable tissues on movement in certain joints and a substantial difficulty in estimating energy losses associated with resistance within the locomotor system [25]. Farley et al. [6] stated that it is impossible to estimate potential elastic energy using the force-displacement curve (ground reaction force with respect to vertical displacement of COM). Indeed, obtaining the actual value of potential elastic energy is impossible in such cases, at least due to the loss of part of the energy (nonmeasurable) in

the form of heat. Furthermore, certain estimations may offer some insight into the phenomenon relating vertical quasi-stiffness and the ability to store potential elastic energy with vertical jump height.

Therefore, the aim of the study is to present a simple method of estimating the potential elastic energy stored as a result of COM lowering during the countermovement phase of the vertical jump. This method uses an instantaneous measurement of the ground reaction force to determine the dependence of the ground reaction force *(F)* on the vertical displacement of COM *(Δy)*.

2. Materials and methods

The study was conducted among 30 able-bodied male university students. The study group was characterized by the following mean parameters (±SD): body height: 1.83 ± 0.08 m, body mass: 80.3 ± 10.4 kg, age: 20 years. The experiments were performed in a Biomechanical Analysis Laboratory (with PN-EN ISO 9001:2009 certification). Before the tests, each participant was familiarized with the research goals, was informed about the purpose of the study and gave written permission for the tests. The study design was approved by the Senate's Research Bioethics Committee, and the procedures complied with the Declaration of Helsinki regarding human experimentation.

Each participant performed 10 single countermovement jumps with arms akimbo (CMJ) to maximal height. Before the test, all study participants underwent an individual warm-up procedure that consisted of continuous shuttle run over a distance of 10 m. The run was performed at a moderate pace of ca. 10 distances per minute and was continued until reaching a heart rate of 150 bpm. Heart rate was measured using a Polar RCX5 GPS Polar pulsometer (Polar Electro, Kempele, Finland). The next step was to record 10 single akimbo CMJs for maximum height. The participant stood upright on a force plate and then maintained the body motionless. At a signal, the athlete performed a vertical jump, preceded by a rapid countermovement of the lower limbs. The palms were resting on the hips throughout the jump. Landing was also performed on the force plate. A 10-second rest took place before single jumps. The length of the interval applied was chosen to ensure that the effect of fatigue on the test result was eliminated [14]. The jump was repeated if the lower limbs were bent at the knee and/or hip joints during the flight phase. The reason for this was that the body

position of the jumper at the moment of landing should resemble as closely as possible that adopted at the time of the feet losing contact with the ground during the take-off. The analysis considered the highest CMJ performed by each participant. A simple spring-mass model was used to simplify the structure of the human motion system. The model assumes that the human body consists of a material point representing the total mass of the body; a massless "spring" representing both lower limbs, which performs the supporting function; and a parallel source of force resulting from the active action of the muscles involved in the take-off [3].

Ground reaction forces *(F)* were measured during CMJs using a Kistler 9281B13 force plate (Winterthur, Swiss). The sampling frequency of the signal from the force plate was 1,000 Hz. BTS SMART Analyzer software (BTS Bioengineering, Milan, Italy) was used to calculate the values of the variables tested. Other calculations were made using a Microsoft Excel 2016 spreadsheet (Microsoft Corporation, Redmont, WA). The instantaneous pattern of changes in the height of COM *(y)* was calculated by double integration of the COM vertical acceleration as calculated from the vertical ground reaction force [8].

The vertical quasi-stiffness ($K = \Delta F / \Delta y$) of the human body was determined as the ratio of the change in the ground reaction force (ΔF) to the corresponding change in the height of COM (Δy), similar to the method described by Struzik and Zawadzki [19]. To reliably estimate quasi-stiffness, it is necessary to determine the relationship $F(\Delta y)$. The slope coefficient for part of the curve $F(\Delta y)$ equals the numerical value of quasi-stiffness in this range. Vertical quasi-stiffness was calculated for the part of the countermovement phase where the slope of the F curve with respect to the Δl axis was relatively constant and the $F(\Delta y)$ profile was nearly linear. There are only these ranges that allow for expression of vertical quasi-stiffness by means of a (single) concrete numerical value [19]. For the countermovement phase, this range was the part between the occurrence of the lowest value of ground reaction force and the lowest location of COM (part of the curve marked green in Fig. 2). This observation holds true only if the value of the coefficient of determination R^2 that expresses the quality of adjustment of the trend line to the relevant part of the $F(\Delta y)$ curve is sufficiently high (over 0.6) [11].

The decrease in the gravitational potential energy of the center of mass (COM) of the body of a person performing a vertical jump during the countermove-

ment phase is partially collected in the form of potential elastic energy by the stretched musculotendinous groups. Therefore, the jump height depends to some extent on the value of the accumulated potential elastic energy. The field under the curve $F(\Delta y)$ represents the qualitative change in the value of gravitational potential energy due to lowering of COM during the countermovement phase (Figs. 1 and 5).
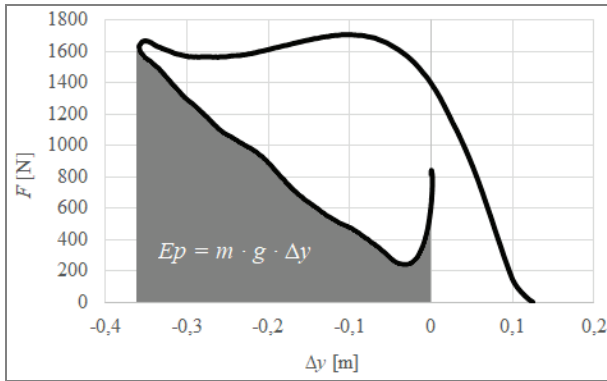

Fig. 1. Ground reaction force (F) depending on the vertical displacement of COM (Δy) in relation to the ground for one of the participants, with the field marked in gray representing the quantitative value of the change in potential gravitational energy (E_p) due to lowering of the jumper's COM in the countermovement phase, where m is body mass, g is the acceleration due to gravity and Δy is the change in COM height
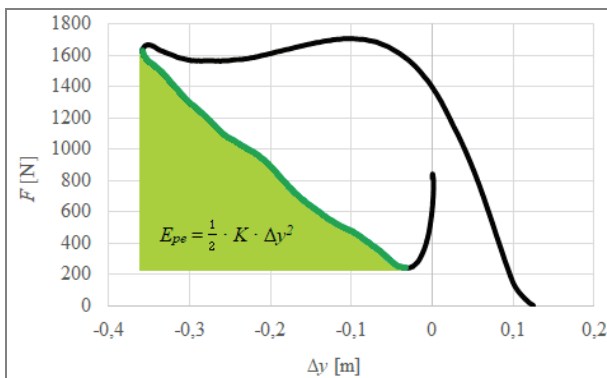

Fig. 2. Ground reaction force (F) depending on the vertical displacement of COM (Δy) in relation to the ground for one of the participants, with the field marked in green representing the quantitative value of the accumulated potential elastic energy (E_{pe}) due to lowering of the jumper's COM in the countermovement phase, where K means the vertical quasi-stiffness and Δy is the change in COM height

Since the body of the person performing the jump does not behave as an ideal spring with linear characteristics, the work done by COM due to the displacement in the countermovement phase (the change in gravitational potential energy E_p) will be greater than the value of the stored (by the "spring" element of the

spring-mass model) potential elastic energy (E_{pe}). Assuming that the shape of the curve $F(\Delta y)$ in the part of the countermovement phase between the lowest value of the ground reaction force and the lowest location of COM is close to linear (the part of the curve marked green in Fig. 2), it is possible to estimate, using Eq. (1), the value of potential elastic energy (E_{pe}) during the depletion of gravitational potential energy (E_p) in the countermovement phase. The relatively constant value of vertical quasi-stiffness in this part of the countermovement phase allows for the use of the value of this variable as the longitudinal stiffness K. Furthermore, the change in COM height was adopted as the displacement Δy (Fig. 2).

$$E_{pe} = \frac{1}{2} \cdot K \cdot \Delta y^2 \qquad (1)$$

The above assumption requires that the dispersion of potential elastic energy (E_{pe}) in the form of heat during the countermovement phase be small, and can be neglected [18].

During a vertical jump, the jumper's COM is lowered during the countermovement phase, accompanied by a decrease in gravitational potential energy. After the beginning of the movement from the standing position in the direction of the gravitational force, the ground reaction force is initially reduced. The ground reaction force is decreased to substantially low values, whereas the body moves nearly inertly with negligible participation of a braking muscular force. It can be assumed that potential elastic energy is not stored in this part of the countermovement phase (the field marked red in Fig. 3).
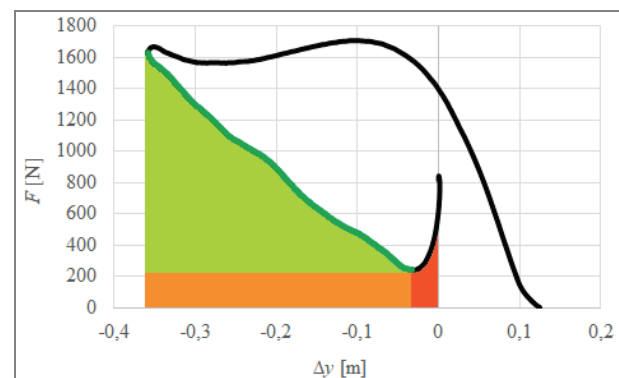

Fig. 3. Ground reaction force (F) depending on the vertical displacement of COM (Δy) in relation to the ground for one of the participants, with the field marked in green representing the quantitative value of the accumulated potential elastic energy (E_{pe}) and the fields marked in yellow and red indicating the remaining loss in potential gravitational energy (E_p) due to lowering of the jumper's COM in the countermovement phase

Next, the ground reaction force starts to increase, which is caused by activation of the muscles engaged in the countermovement phase (mainly eccentric activity of the knee joint extensors). Therefore, it becomes possible to collect potential elastic energy in musculotendinous units. Part (~1/2) of the gravitational potential energy is transformed into the kinetic energy of the lowered COM (E_k in Fig. 4), and at the same time, the remaining part begins to accumulate in the form of internal elastic energy in the stretched tissues. The transformation of gravitational potential energy into kinetic energy continues until the maximal velocity of COM lowering in the countermovement phase is reached (point v_{max} presented in Fig. 4). Next, the countermovement is decelerated, and kinetic energy (the field shown in Fig. 4 in blue) is transformed into potential elastic energy (the field shown in Fig. 4 in green) [18].
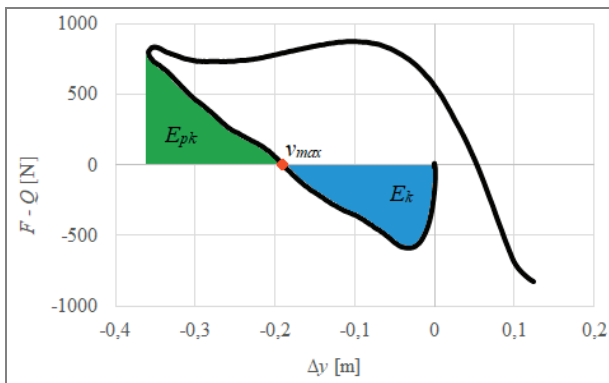

Fig. 4. Difference between ground reaction force and participant weight ($F - Q$) with respect to the vertical displacement of COM (Δy) relative to the ground. The field marked in blue (E_k) is the quantitative value of the kinetic energy obtained by converting part of the gravitational potential energy through the lowering of COM, the field marked in green (E_{pk}) is the part of the potential elastic energy accumulated through the conversion of kinetic energy, and (v_{max}) is the point at which the jumper's COM reaches its maximum velocity in the countermovement phase

The storage of potential elastic energy occurs until the maximal lowering of COM. The value of accumulated potential elastic energy is the highest when the lowest position of COM is reached during the vertical jump.

The interpretation of energy conversion presented in Fig. 4 results from the fact that the loss in potential gravitational energy due to the decrease in COM of the jumper in the countermovement phase can be presented as a product of the weight and the change in the vertical displacement of COM (presented in Fig. 5) and as a field under the curve $F(\Delta y)$ in the countermovement phase (as in Fig. 1).

Hence, the blue (E_k) and green (E_{pk}) fields shown in Fig. 4 are equal. Therefore, the following transformations of energy are observed during the countermovement phase of the vertical jump:
– the loss of potential gravitational energy (E_p) is partly converted into kinetic energy (E_k), potential elastic energy (E_{pe}) and a third form, which can be associated with energy losses or "negative" work due to the braking effect of skeletal muscles (fields in Fig. 3 marked in orange and red);
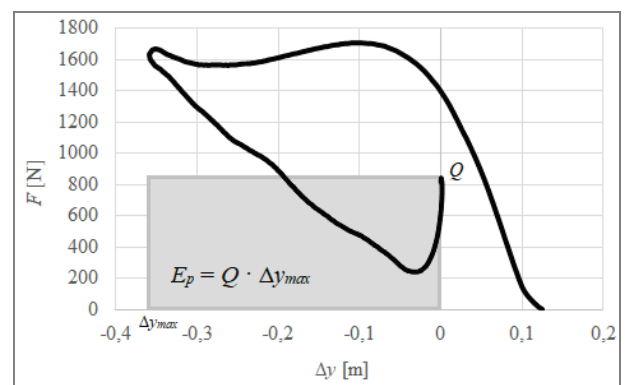– kinetic energy (E_k) is converted into potential elastic energy (E_{pk}) [18].

Fig. 5. Ground reaction force (F) depending on the vertical displacement of COM (Δy) in relation to the ground for one of the participants, with the field marked in gray representing the change in potential gravitational energy (E_p) due to the lowering of the jumper's COM in the countermovement phase. Q denotes body weight, and Δy_{max} is the maximum vertical displacement of COM

3. Results

The mean value ($\pm$SD) of the total change in gravitational potential energy due to lowering of COM during the countermovement phase of a vertical jump was $E_p = 240 \pm 58$ J. Furthermore, the value of potential elastic energy collected due to the lowering of COM was $E_{pe} = 183 \pm 69$ J (76.2% of E_p). A total of 24.3% of the value of E_{pe} can be considered part of the potential elastic energy ($E_{pk} = 44 \pm 21$ J) that comes from the transformation of kinetic energy. The value of E_{pk} accounted for 18.5% of E_p.

Furthermore, the values of other variables were as follows: $K = 5.1 \pm 1.4$ kN/m, $\Delta y = 0.269 \pm 0.055$ m.

4.Discussion

With too slow (insufficiently dynamic) a countermovement with the lower limbs during a vertical jump, elastic energy accumulated during the eccentric phase (the countermovement) will be dissipated, e.g., in the form of heat [2], [5], [25]. Therefore, the benefits resulting from the execution of the countermovement immediately before take-off will be partially lost. The difference (57.1 ± 44.5 J) between the change in gravitational potential energy due to the lowering of COM and the potential elastic energy found in this study may represent a loss of heat (or part thereof) occurring during the vertical jump phase. The half-life of the potential elastic energy stored in the deformed muscle tissue is 0.85 s, and after four seconds, the energy is completely dissipated [23]. Therefore, a time of longer than one second between muscle stretching and contraction causes the muscle to stop behaving like a "spring" and lose, to a large extent, its ability to use the potential elastic energy [6], [23]. In such case, the jump is performed as if it were made from a fixed static position under isometric muscle contraction (like an SJ rather than a CMJ), which has a negative impact on the height [1], [5], [16]. A critical moment in a vertical jump that determines the use of the benefits of the stretch-shortening cycle is the transition between the phases of countermovement and take-off. During movement tasks aimed at reaching a high final velocity of body movement (such as a vertical jump), changes in the directions of movement during the stretch-shortening cycle should occur in the shortest time possible while maintaining an "optimal" range of countermovement. Each delay or slowdown reduces the contribution of elastic energy to the energy balance in muscles in the concentric phase of the movement [16], [17].

Bober [4] estimated the range of desired values of maximum flexion in the hip joints (70°–105°) and the knee joint (78°–92°) during the countermovement phase in a CMJ. With a deep countermovement, the duration of the jump may be too long to fully utilize the stored potential elastic energy (without significant losses in the form of heat). On the other hand, with too narrow countermovement, the lower limb extensors may be insufficiently stretched before the contraction, which will be reflected by the value of the collected potential elasticity energy. According to Eq. (1), the accumulated potential elastic energy is a quantity directly proportional to the square of the change of length. Therefore, the potential elastic energy is theoretically obtained mainly by means of the change in the length of the "spring" that represents the lower limbs and, to a lesser extent, through the increase in stiffness [20]. It is necessary to perform the countermovement with the appropriate range of motion in the lower limb joints to achieve the maximum possible final velocity of take-off, thus ensuring an "optimal" movement technique. Consequently, performing a correct countermovement with the lower limbs (with adequate depth) is critical to the achievement of maximal vertical jump performance [9], [18].

Liu et al. [15] used the field under the ground reaction force curve (relative to body weight) as a function of the vertical displacement of COM in the countermovement phase (similarly to Fig. 1) to estimate the potential elastic energy value. The type of jump analyzed was a CMJ without an arm swing. The assumption, however, that the entire loss in potential gravity energy due to the decrease in COM of the jumper in the countermovement phase is converted into potential elastic energy appears to be too simplistic. Therefore, the values of potential elastic energy obtained by Liu et al. [15] can be considered to be overestimated and related to the total loss in potential gravitational energy. Indeed, the values of "potential elastic energy" obtained by young healthy male participants (age: 24.3 ± 2 years, energy stored: 248.9 ± 35 J) were close to the change in gravitational potential energy obtained in the present study (240 ± 58 J). Furthermore, Liu et al. [15] examined a group of elderly healthy male participants (age: 68.6 ± 5 years) who reached a "potential elastic energy" value of 195.4 ± 68.7 J. It can therefore be assumed that the ability to accumulate potential elastic energy decreases with age [15], although this statement will be true only for a similar technique of performing a vertical jump (similar level of deformation in the countermovement phase in both groups) [20].

The potential elastic energy accumulated by pliable tissues in the countermovement phase of a vertical jump is derived from the potential gravitational energy, with the value of the latter decreasing as a result of lowering the jumper's COM. Part of this potential gravitational energy is converted into elastic energy stored through the elongation of pliable tissues. Another part of the potential gravitational energy is converted into kinetic energy associated with the movement of the lowering of COM (field E_k in Fig. 4). The next part of the change in potential gravitational energy in the countermovement phase is transferred in the form of "negative" work performed by skeletal muscles, actively inhibiting the lowering of COM (orange and red fields on Fig. 3). This muscle activity determines the depth of the countermovement and at the same time determines what part of the potential gravitational energy is transformed into elastic energy.

The kinetic energy E_k stored in the first part of the countermovement phase (Fig. 4) is transformed in the second part of the countermovement into another portion of elastic energy (E_{pk} in Fig. 4), and with this energy conversion, the ground reaction force in the final part of the countermovement phase can reach values exceeding the body weight Q. With this increase in the ground reaction force, a substantial vertical acceleration (higher than zero) in the jumper's COM is observed from the beginning of the take-off phase. This is one of the beneficial effects of performing a take-off preceded by a countermovement. Anderson and Pandy [2] stated that the storage and utilization of elastic energy enhance jumping efficiency much more than overall jumping performance.

It is important to realize that the spring-mass model represents the behavior, not the structure, of the integrated musculoskeletal system during bouncing gaits. In reality, the length change in the leg spring that occurs during the ground contact phase corresponds to joints flexing and extending [7]. Since the vertical quasi-stiffness in the part of the countermovement phase between the lowest value of the ground reaction force and the lowest location of COM is relatively constant, it is possible to estimate the value of the percentage of potential elastic energy during the depletion of gravitational potential energy in the countermovement phase of the vertical jump. The above assumption requires that the distribution of potential elastic energy in the form of heat be insignificant and can be neglected. Charts analogous to the chart presented in Fig. 2 have been previously obtained by various authors [1], [6], [7], [8], [11], [12], [19]. However, estimation of potential elastic energy based on these charts has not often been performed in practice, although force-displacement curve can also be used to determine the jump height [10]. The height of the vertical jump is related to the force-displacement curve [12]. It should also be noted that this evaluation of potential elastic energy is only an estimation and is very rough. By analogy, the calculation methodology presented in our study can be successfully used for the estimation of potential elastic energy during other movements, including commonly examined motions such as walking, running and other jumping tasks.

5. Conclusions

Using the force-displacement curve allows for estimation of the value of the potential elastic energy accumulated during the countermovement phase of a vertical jump. It should be noted that the presented estimation of potential elastic energy is only general and rough. However, certain estimations of potential elastic energy may offer some insight into the phenomenon relating vertical quasi-stiffness and the ability to store potential elastic energy with vertical jump height.

Acknowledgements

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