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Leg stiffness adjustment during hopping at different intensities and frequencies

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Understanding leg and joint stiffness adjustment during maximum hopping may provide important information for developing more effective training methods. It has been reported that ankle stiffness has major influence on stable spring-mass dynamics during submaximal hopping, and that knee stiffness is a major determinant for hopping performance during maximal hopping task. Furthermore, there are no reports on how the height of the previous hop could affect overall stiffness modulation of the subsequent maximum one. The purpose of the present study was to determine whether and how the jump height of the previous hop affects leg and joint stiffness for subsequent maximum hop.

Ten participants completed trials in which they repeatedly hopped as high as possible (MX task) and trials in which they were instructed to perform several maximum hops with 3 preferred (optimal) height hops between each of them (P3MX task). Both hopping tasks were performed at 2.2 Hz hopping frequency and at the participant's preferred (freely chosen) frequency as well.

By comparing results of those hopping tasks, we found that ankle stiffness at 2.2 Hz ($p = 0.041$) and knee stiffness at preferred frequency ($p = 0.045$) was significantly greater for MX versus P3MX tasks. Leg stiffness for 2.2 Hz hopping is greater than for the preferred frequency. Ankle stiffness is greater for 2.2 Hz than for preferred frequencies; opposite stands for knee stiffness.

The results of this study suggest that preparatory hop height can be considered as an important factor for modulation of maximum hop.

Key words: *joint stiffness, jumping performance, preferred hopping frequency, spring-mass model*

1. Introduction

The whole body during hopping and running is often modeled with a "spring-mass model" which consists of a body mass supported by a spring [4], [6]. One of the most important variables that reflect mechanical properties and some coordination issues of leg spring is leg stiffness, defined as the ratio of maximum ground reaction force to maximum leg (spring) compression in the middle of the stance phase [6], [22]. While previous research suggested importance of leg stiffness as a mechanical variable which has significant influence on movement performance [13], [21], [26], some authors considered leg stiffness as a global performance variable, where joints simultaneously coordinate during movement perturbations for the purpose of stabilizing and controlling leg kinematics [3], [5], [9].

Hopping is an excellent model for perturbation experiments to test how joints are coordinated in order to enable stable spring-mass dynamics during maximum jumping performance. Further, hopping could simulate the movement which is used in many sports techniques and training regimes. Therefore, the examination of how activity that precedes the maximum

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hop influences its stiffness modulation, could give important knowledge for training activity – improving performance and injury prevention.

Leg stiffness appears to be sensitive to hopping height and hopping frequency, since it increases with increasing each of them [6], [10]. Among other things, this paper draws attention to two hopping parameters that might heavily influence stiffness increase at the given hopping frequency: ground contact time and the height of the previous hop (i.e., preparatory hop).

First, in order to increase hopping height, aerial time has to be increased, i.e., ground contact time has to be reduced as much as possible. In relation to this, theoretical model and experimental results showed that contact time is a critical parameter with the greatest influence on leg stiffness [1], [23]. To achieve ground contact time reduction, modulation of joint stiffness has to be engaged. There are reports claiming that modulation of ankle stiffness is the primary mechanism for increasing leg stiffness when humans hop to different heights [8]. In contrast to that, during freely chosen (i.e., preferred) hopping frequency, knee stiffness takes the role of major determinant for hopping performance [20]. This led us to the assumption that time (frequency) constraints determine strategy for adjusting stiffness during hopping in place.

Second, previous studies suggested that neuromuscular and mechanical properties of locomotor system have fine tuning for different drop heights in drop jump tasks [1], [30], [16]. According to some kinematic similarities between hopping and drop jumps noticed by Hobara et al. [13] it seemed justified to suggest that jump height of the previous hop (the highest point of the center of mass during the flight phase of the previous hop, which is analogous to drop height in drop jump task) could influence movement mechanics of the hop that follows. Based on this, we anticipated that humans might adopt different strategy to adjust leg stiffness by changing hopping height of the previous hop. In order to analyse and measure this effect we prepared two hopping tasks with the purpose to control different heights of center of mass before the maximum hop. Both tasks were to be performed in constrained and preferred hopping frequency conditions.

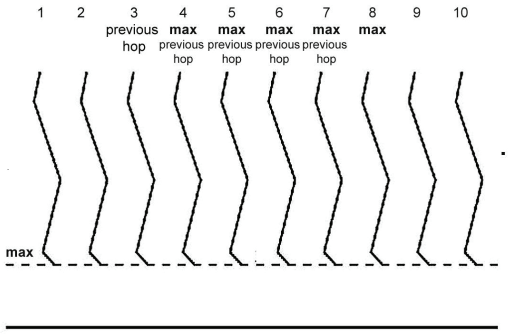
The main purpose of the present study was to determine whether the slight modification of the experimental task affects leg stiffness and the underlying joint biomechanics for the maximum hops. This modification concerns variations in heights of the center of mass for the hop/hops that preceded maximum one. Also, as the leg stiffness depends on the stiffness of torsional joint spring, some studies indicated that jumping mechanics is sensitive to changes in ankle joint stiffness during submaximal hopping with short contact time [7], [8], [11], whereas the role of knee joint stiffness is more related to the jumping intensity (performance) in maximal hopping tasks [14], [20]. Based on this, it could be expected that during different hopping tasks, some biomechanical parameters of the jump will primarily be modulated by the knee [12], [14], [20] or ankle stiffness [7], [8], [11].

2. Materials and methods

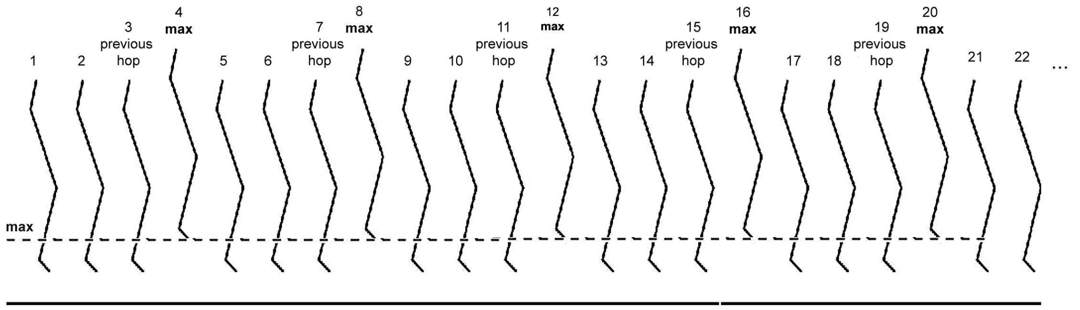
Ten healthy male non-professional athletes with no neuromuscular disorders participated in the study (4 volleyball players and 6 basketball players). Their physical characteristics were: age between 21±1.2 years, height 189.2±3.1 cm, and body mass 81.1±3.5 kg (arithmetic mean ± SD). Informed consent approved by the Human Ethics Committee, Faculty of Sport and Physical Education, University of Belgrade, was obtained from all participants before the experiment.

Participants were instructed to hop barefoot on a force plate with hands on their hips, following the beat of a metronome set at the frequency 2.2 Hz, approximately the preferred frequency for human hopping in place at which maximum efficiency and minimum energy expenditure is observed [6]. Also, frequency of 2.2 Hz was chosen because the hopping at frequency below this one typically does not display spring-like leg behavior [6]. Further on, the participants were allowed to optimize their own jumping technique by hopping at their preferred rate ("preferred hopping frequency" – PHF), without the metronome beat.

To test the hypothesis, the testing procedure included two different hopping tasks in order to achieve different heights of the hop that precedes maximum one. Hop height was defined as the highest point of the center of mass during the flight phase. In the first hopping task the only instruction given to the participants was to make each hop as high as possible (maximum height hopping – MX) (Fig. 1a). In the second hopping task, the participants were instructed to alternately perform preferred and maximum hop heights. Therefore, the participants repeatedly performed three hops on their optimal hop height followed by the one maximum height hop (three preferred hops followed by one maximum height hop – P_3MX) (Fig. 1b). The performance goal for all maximum jumps in both tasks was to achieve the maximum height with as short contact time as possible.



a) MX task



b) P_3MX task

Fig. 1. The illustration of the two different hopping proposed: (a) maximum height hopping (MX) and (b) preferred-maximum-preferred height hopping (P_3MX). Note for the last four maximum hops (numbers 5, 6, 7 and 8) of the MX task, that maximum hop was also taken as a previous one for the subsequent hop

In the MX task, the participants performed 15 hops and only five of them from the very middle of the task were used for analysis. In the P_3MX task, the participants performed 25 hops, where only five maximum hops (the fourth, the eighth, the twelfth, the sixteenth and the twentieth hop) were used for the analysis. Hops at a preferred height were excluded. Approximately 20 hops (2 frequencies, 5 hops per frequency, 2 hopping tasks) were analyzed per participant.

All participants attended a test familiarization session two days before the testing session. Then, during the testing session, they performed different hopping tasks, with a four to five minute rest period between each performance. After the collection of the data, only the hops within ±3% of the desired hopping frequency (2.2 Hz) were included in our analysis [3].

Hopping was performed on a multi-axis AMTI force plate (60 × 120 cm). Vertical ground reaction force (GRF) was sampled at 1000 Hz. Each participant was videotaped in the sagittal plane at 240 frames per second using a high speed Qualisys ProReflex MCU 240 motion capture camera. We placed six retro reflective markers on the participants at the following locations: the tip of the first toe, the fifth metatarsophalangeal joint, the lateral malleolus, the lateral epicondyle of the femur, the greater trochanter, and the acromion scapulae. Kinematic data were low-pass filtered by a fourth-order zero-lag Butterworth filter with a cut-off frequency of 8 Hz.

Leg stiffness was calculated as the ratio of peak vertical GRF to peak leg compression in the middle of the ground contact phase [8]. Joint stiffness was calculated as an average torsional stiffness obtained by dividing the peak joint moment by angular displacement calculated from the beginning of the ground contact to the maximum joint flexion [8]. Leg and joint stiffness calculation was based on the assumption that the timing of peak GRF occurred at the instant of the lowest position of the center of mass (COM) and simultaneously with the peak joint moments and maximum joint flexions. Calculations were done according to the procedures that were presented in previous researches [7], [8], [14].

One-way repeated measure ANOVA and LSD post-hoc multiple comparison test were performed to test several dependent biomechanical variables between two different maximum hopping tasks: MX and P_3MX. This statistical procedure was repeated for constrained hopping frequency and preferred hopping frequency. For the sake of simplicity of experimental design, we focused on testing a single factor – height of the previous hop achieved during different hopping tasks, and its effects on participant's biomechanical variables. Statistical significance was set at $p \leq 0.05$.

SPSS software (Version 17.0, SPSS Inc.) was used for all statistical analysis.

3. Results

For constrained frequency condition, all participants successfully performed both motor tasks and were able to follow the beat of a metronome (Table 1). The participants also performed hopping at their preferred frequencies, approximately achieving ~1.43 and ~1.81 Hz, for MX and P_3MX tasks, respectively.

Figure 2 shows typical examples of the relationship between GRF and COM displacement, recorded from one participant. Leg compression started at touchdown and is represented by the ascending part of the COM-GRF diagram. The GRF peaked at the moment of maximum leg compression (middle of the stance phase), and subsequently, the GRF decreased with extension of the leg until take-off. Since the slope of the diagram denotes leg stiffness, it is evident that there is no significant difference between MX and P_3MX hopping tasks for both hopping frequencies: 2.2 Hz ($p = 0.691$) and preferred ($p = 0.807$) (Fig. 2 and Table 1).

Figure 3 shows typical examples of the relationship between joint torque and angular displacement of the ankle and the knee joint, recorded from one participant. Angular displacement was defined as the change in joint angle relative to the instant when the feet hit the ground. The average slope of the "joint torque–angular displacement" relationship can be thought of as the average joint stiffness.

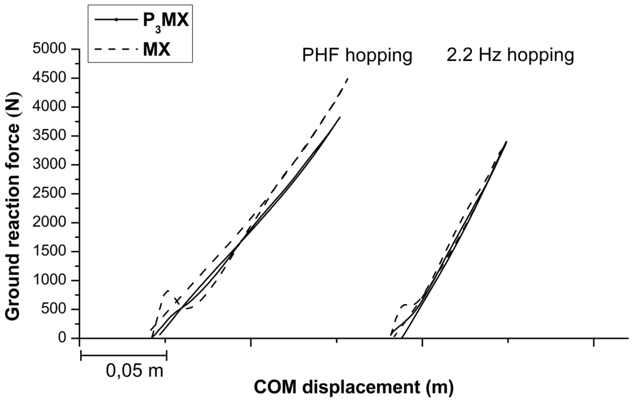


Fig. 2. Typical examples of GRF-COM displacement curves, recorded from one participant in a single hopping cycle at constrained (2.2 Hz) and preferred hopping frequencies (PHF), for both hopping tasks: MX (maximum height hopping) and P_3MX (three preferred hops followed by one maximum height hop). Note that the curve shift along the COM axis, does not correspond to initial COM position

At 2.2 Hz hopping, ankle stiffness was significantly greater in MX than in the P_3MX task ($p = 0.041$, re-

Table 1. Data for MX (maximum height hopping) and P_3MX (three preferred hops followed by one maximum height hop) tasks, for constrained frequency hopping (2.2 Hz) and preferred hopping frequency (PHF). (Mean values and standard deviations of the means are presented. Note that only maximum hops were analysed for P_3MX task)

	2.2 Hz hopping			PHF hopping		
	MX		P_3MX	MX		P_3MX
Hopping frequency (Hz)	2.22 (0.03)		2.25 (0.06)	1.43 (0.13)		1.81 (0.21)
Ground contact time (ms)	175.8 (15.4)		172.6 (12.5)	196.8 (25.4)		210 (30.09)
Hopping height (m)	0.11 (0.02)	†	0.13 (0.02)	0.36 (0.08)	*	0.29 (0.12)
Vertical take off velocity (ms-1)	1.48 (0.11)	†	1.61 (0.13)	2.62 (0.29)	*	2.32 (0.47)
Peak GRF (N)	4076.4 (265.9)	†	4427.7 (252)	5098.2 (428.7)	†	4416 (494.04)
Leg compression (m)	0.061 (0.006)	*	0.067 (0.011)	0.09 (0.03)		0.09 (0.02)
Leg stiffness (kN/m)	54.6 (8.6)		55.6 (10.3)	41.3 (9.6)		43.1 (6.8)
Ankle angle at touchdown (rad)	2.168 (0.215)	*	2.084 (0.164)	2.260 (0.129)	†	2.084 (0.127)
Knee angle at touchdown (rad)	2.754 (0.127)	†	2.552 (0.164)	2.702 (0.171)	†	2.497 (0.124)
Hip angle at touchdown (rad)	2.923 (0.092)	†	2.786 (0.089)	2.888 (0.044)	†	2.751 (0.056)
Ankle peak moment (Nm)	573 (159.3)		566.4 (150)	547.3 (247.1)		473.9 (198.3)
Knee peak moment (Nm)	241.2 (42.4)	*	372 (138.5)	564 (177.5)		515.9 (152.4)
Hip peak moment (Nm)	412.3 (99.9)		480.8 (133.9)	611.6 (145.2)	†	418.9 (69.1)
Ankle angular displacement (rad)	0.584(0.183)	*	0.778 (0.096)	0.990 (0.082)		1.030 (0.085)
Knee angular displacement (rad)	0.382 (0.120)	†	0.625 (0.124)	0.726 (0.105)	†	0.856 (0.143)
Hip angular displacement (rad)	0.178 (0.054)	†	0.368 (0.099)	0.373 (0.080)	†	0.513 (0.131)
Ankle stiffness (Nmrad-1)	948.1 (245.2)	*	780 (218.1)	561.03 (258.4)		468.2 (204.9)
Knee stiffness (Nmrad-1)	616.8 (175.9)		577.7 (174.3)	845.1 (256.8)	*	617.3 (188.04)
Height of the previous hop (m)	0.11 (0.01)	†	0.08 (0.01)	0.35 (0.04)	†	0.15 (0.02)

(†) denotes a statistically significant difference between MX and P_3MX hopping at ($p < 0.01$).
(*) denotes a statistically significant difference between MX and P_3MX hopping at ($p < 0.05$).

spectively) (Table 1). Knee stiffness was significantly greater in MX than in the P$_3$MX task, only at preferred hopping frequency ($p = 0.045$).

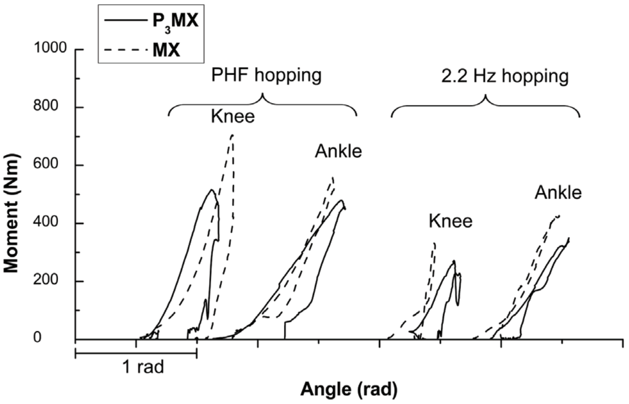


Fig. 3. Typical examples of moment–angular displacement curves of the ankle and knee, recorded from one subject in a single hopping cycle at constrained (2.2 Hz) and preferred hopping frequencies (PHF), for both hopping tasks: MX (maximum height hopping) and P$_3$MX (three preferred hops followed by one maximum height hop)

By analysing stiffness results given in Table 1, we found that:

(a) leg stiffness for 2.2 Hz hopping is greater than for the preferred frequency, although that was expected;
(b) ankle stiffness is greater for 2.2 Hz than for preferred frequencies; opposite stands for knee stiffness;
(c) at 2.2 Hz hopping, ankle stiffness was significantly greater for the MX than for the P$_3$MX task ($p = 0.041$);
(d) at preferred frequency, knee stiffness was significantly greater for the MX than for the P$_3$MX task ($p = 0.045$).

For the hip joint, however, the phase shift between the peak angular displacement and peak joint moment was more than 10% in most of the hopping conditions. This has been used as an exclusion criterion earlier [7], [20], and therefore, hip joint stiffness was not calculated in the present study.

At 2.2 Hz (Table 1), peak GRF was approximately 8.6% greater for the P$_3$MX than for the MX task ($p = 0.005$). Accordingly, leg compression showed similar trend of 9.8% increase in the case of P$_3$MX versus MX task ($p = 0.036$).

On the other hand, for the preferred frequency (Table 1), we observed that peak GRF was 15.4% greater for the MX than for the P$_3$MX task ($p = 0.000$) and there was no difference for leg compression between these two tasks ($p = 1.000$).

Ankle, knee and hip joint angles at touchdown were greater for MX compared to P$_3$MX task, across both hopping frequencies ($p \leq 0.01$) (Table 1).

As was expected, height of the previous hop was significantly greater for MX than for the P$_3$MX task ($p \leq 0.01$), for both frequencies (2.2 Hz and PHF) (last row in Table 1).

4. Discussion

The purpose of the study was to examine the influence of a hop height that preceded maximum hop on a leg and joint stiffness adjustment in maximum one. As can be seen from the results, leg stiffness remained unchanged for both hopping tasks under the same hopping frequency. Increased height of the hop that preceded maximum one, notably increased ankle joint stiffness only at the constrained frequency (2.2 Hz) and also increased knee joint stiffness only at preferred frequency (PHF). The results of this study showed that slight modification of the experimental task, i.e., modification of the hopping regime, significantly influenced the stiffness properties of a spring-mass model.

This study proved that at constrained frequency hopping (2.2 Hz), the least stiff spring (ankle joint) was highly influenced by the hopping tasks (the P$_3$MX task showed lower ankle stiffness than the MX task) and that indicated that in a system with multiple springs, the least stiff spring undergoes the largest angular displacement in response to different motor tasks [7]. If we recall that in the P$_3$MX task, participants were allowed to perform 3 optimal preparatory hops before they perform maximum one, it is evident that they were able to adapt the whole system for the upcoming maximal hop and do not just heavily rely on the ankle joint as is the case in the MX task. This strategy caused higher hopping heights, greater range of motions of ankle joint and smaller ankle stiffness for the P$_3$MX task vs MX task at 2.2 Hz hopping (Table 1). One possible explanation could be the following: the effective catapult action in tendinous tissue of the short-contact stretch-shortening cycle movement can be limited by the insufficient drop intensity [18], so in the P$_3$MX task where lower height of the previous hop (analogous to drop intensity) compared to MX task was noted (Table 1), participants tended to compensate the limit through setting several biomechanical parameters that should provide the movement effectiveness. Thus, greater range of motion in the ankle joint influenced the longer duration of the force applied by the foot on the surface and slower muscle contraction of the triceps surae [29], both of which led to greater ground reaction force (GRF) in P_3MX task compared to MX (Table 1). This study suggested that the modulation of ankle stiffness could be one of the crucial variables for changing the performance of hopping tasks in constrained frequency conditions and lower eccentric loads.

This study also proved that knee stiffness was greater in the MX task compared to P_3MX for both constrained and PHF hopping tasks, but significant difference was noticed only for PHF task. This result is in accordance with previous studies [14], [20], in which it was shown that knee stiffness increases with hopping intensity. As expected, our results have shown that participants had smaller knee angular displacement during the ground contact for MX compared to P_3MX task. Considering that participants achieved much higher hopping heights at PHF hopping compared to hopping in constrained conditions at 2.2 Hz (3.27 and 2.23 times for MX and P_3MX tasks, respectively, Table 1), it was expected that they had to utilize much "stiffer" jumps [16]. Although overall leg stiffness in PHF hopping is considerably smaller than in constrained conditions (Table 1), stiffer jumps have been performed at the expense of increased knee stiffness – greater knee moment as a consequence of higher GRF and greater knee angular displacement [14], [20] (Table 1). This is consistent with expected participant's behavior, where they primarily had to utilize knee extensor muscles at the expense of ankle ones: longer muscle fibers, larger muscle volume and greater peak muscle force [15].

Hip joint stiffness at P_3MX task did not show linear spring characteristics, because phase shift between the peak joint moment and peak angular displacement was significant (higher than 10%). This might be a tendency of the participants to implement mostly concentric contraction in leg extensor muscles, including higher rotation of proximal segments – trunk (which involves higher rotational energies compared to distal segment). This is a typical movement strategy in the conditions where maximum hop was performed after insufficient eccentric load that could provide effective catapult action of muscle-tendon complex during short-contact stretch-shortening cycle based movement (P_3MX task).

Despite the fact that participants in the P_3MX task of the PHF hopping condition had adjusted their hopping frequency and preparatory hopping height for the main purpose to make the maximum hop as high as possible, in the MX task participants achieved much higher maximum hop heights. Previous research showed that different pre-stretch loads have a considerable influence on the process of storage and subsequent recoil of the elastic deformation energy during stretch-shortening cycle locomotion [17]. That result led us to the assumption that the height of the previous hop in the P_3MX task (around 15 cm) represented insufficient eccentric load for muscle-tendon complex to realize an adequate stretch-shortening cycle action, contrary to the height of the previous hop in MX task (around 35 cm) (Table 1). In addition, it is worth noting similarities between values for height of the previous hop in the MX task at preferred frequency (~35 cm) and values for optimal platform height for drop jumps (40–60 cm) from which the highest rebound is performed [2], [19], [24], [25]. In the P_3MX task on self-selected frequency (PHF hopping), the participants tended to realize lower hopping height during the preparation phase in order to produce lower muscle work. Based on previous observations [6], [28], we came to conclusion that despite the fact that instruction given to participants for the P_3MX task at the PHF hopping was to adjust the preparatory hopping frequency and hopping height for maximum hops, the primary mechanism for hopping frequency and hopping height adjustment in these conditions was the energy saving mechanism.

Our main assumption that ankle and knee stiffness of the maximal hop depends on the height of the previously derived one, whether hopping is performed in constrained or preferred frequency conditions, has been confirmed and explained. The results of this study suggest that the height of the hop that preceded the maximum one can be considered as an important factor and its influence is reflected as: (a) increased engagement of ankle joint in constrained frequency condition (2.2 Hz task, Table 1), (b) increased engagement of knee joint in conditions where participants were allowed to optimise their hopping frequency (PHF task, Table 1), and (c) no influence on the overall leg stiffness (Fig. 2 and Table 1). These results, together with some previous results, highlight the assumption that locomotor system has a subtle strategy to control overall stiffness during different hopping intensities and that the control mechanism can be monitored by using general spring-mass model [20], [27].

The findings obtained in our study can be practically applied in plyometric training method. The results showed that inter-relationship between the time limitation (hopping frequency) and the magnitude of eccentric loading (hopping height) in a stretch-shortening cycle of hop based movements requires engagement of different lower extremities muscle groups and that should be taken into account when the instructions are being given to athletes. If the only instruction given to athletes refers to a hopping intensity level (such as achieving different hopping heights), knee joint will play the dominant role among other leg joints, so it will cause greater loading of the knee extensor muscles. Consecutive hopping at maximum intensity level will augment this effect. Thus, by hopping at preferred frequency, subjects will gain almost 25% greater maximum hopping heights if the preparatory hops had been performed at maximum level, compared to preparatory hops performed at their optimum level. Instructions that had been given to participants to raise their hopping frequency (at 2.2 Hz in our analysis) reflected particularly on ankle joint engagement by increasing their stiffness and load of the supporting muscles. Although ankle joint plays a major role in maximum hopping at 2.2 Hz, it seems that body system has a subtle mechanism to adapt itself and gain maximal hopping heights (~18% greater) in cases when preparation hops are not maximal too, but of a participant's optimal kind.

Acknowledgments

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