Original article (short paper)

Vertical jump fatigue does not affect intersegmental coordination and segmental contribution

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Abstract—The aim of this study was to describe the intersegmental coordination and segmental contribution during intermittent vertical jumps performed until fatigue. Seven male visited the laboratory on two occasions: 1) the maximum vertical jump height was determined followed by vertical jumps habituation; 2) participants performed intermittent countermovement jumps until fatigue. Kinematic and kinetic variables were recorded. The overall reduction in vertical jump height was 5,5%, while the movement duration increased 10% during the test. The thigh segment angle at movement reversal significantly increased as the exercise progressed. Non-significant effect of fatigue on movement synergy was found for the intersegmental coordination pattern. More than 90% of the intersegmental coordination was explained by one coordination pattern. Thigh rotation contributed the most to the intersegmental coordination pattern, with the trunk second and the shank the least. Therefore, one intersegmental coordination pattern is followed throughout the vertical jumps until fatigue and thigh rotation contributes the most to jump height.

Keywords: intermittent exercise, principal component analysis, psychomotor performance

Resumo—"Fadiga em salto vertical não afeta a coordenação intersegmental e contribuição segmental." O objetivo deste estudo foi descrever a coordenação entre segmentos e suas contribuições durante saltos verticais intervalados realizados até a fadiga. Sete indivíduos visitaram o laboratório em duas ocasiões: 1) foi determinada a altura máxima do salto vertical e realizada familiarização com saltos verticais; 2) participantes realizaram saltos verticais em contramovimento até a fadiga. Foram coletadas variáveis cinemáticas e cinéticas. A altura do salto vertical reduziu 5,5% e duração do movimento aumentou 10%. O ângulo da coxa no instante de reversão do movimento aumentou durante o exercício. A fadiga na sinergia do movimento não influenciou na coordenação intersegmental. Acima de 90% da coordenação entre segmentos foi explicada por um padrão coordenativo. A rotação da coxa foi o que mais contribuiu com o padrão coordenativo, seguido pelo tronco e perna. Portanto, em saltos verticais realizados até a fadiga, a coordenação intersegmental é mantida e a rotação da coxa tem maior contribuição na altura do salto.

Palavras-chave: exercício intervalado, análise do componente principal, desempenho psicomotor

Resumen—"Fatiga salto vertical no afecta a la coordinación entre segmentos y la contribución segmentaria." El objetivo fue describir la coordinación entre los segmentos y sus contribuciones durante los saltos verticales realizadas hasta la fatiga. Siete sujetos visitaron laboratorio dos ocasiones: 1) determinó la máxima altura en el salto vertical y amistad con los saltos verticales; 2) participantes completaron saltos verticales contramovimento la fatiga. Se recogieron las variables cinemáticas y cinéticas. La altura del salto vertical disminuyó 5,5% y la duración del movimiento se incrementó 10%. El ángulo del muslo en instante de inversión del movimiento aumentó durante ejercicio. No hubo efecto de fatiga en sinergia de movimiento para la coordinación de movimientos. Más del 90% de coordinación entre sectores ha sido explicado por un patrón coordinativo. La rotación del muslo fue mayor contribuyente la coordinación de movimientos, seguido por tronco y piernas. En los saltos verticales realizados hasta la fatiga se mantiene coordinación entre segmentos y rotación del muslo tiene mayor contribución en altura del tacón.

Palabras clave: año de intervalo, análisis de componentes principales, comportamiento psicomotor

Introduction

Vertical jumping is an essential component of several sports. As such, this motor skill is frequently performed leading to fatigue. It is known that vertical jumping-induced fatigue alters muscle properties (Bojsen-Moller, Magnusson, Rasmussen, Kjaer, & Aagaard, 2005; Ishikawa, *et al.*, 2006b) and, consequently, the ability to generate maximum or near maximum joint torques. However, a high vertical jump performance (i.e., jumping height) requires optimization of the movement coordination; that is, tuning control of the musculoskeletal properties (Bobbert, Krogt, Doorn, & Ruiter, 2011). Therefore, fatigue may be a trigger to the central nervous system to modify the intersegmental body coordination responsible for vertical jump performance (van Ingen Schenau, van Soest, Gabreels, & Horstink, 1995).

The effect of fatigue on movement coordination has already been investigated during jumping adapted conditions in sledge apparatus (Horita, Komi, Hamalainen, & Avela, 2003; Horita, Komi, Nicol, & Kyrolainen, 1999; Kuitunen, Avela, Kyrolainen, Nicol, & Komi, 2002). It has been reported a decreased knee and ankle power after continuous rebounds and no changes in the contribution of the lower limb joints' extension, even under decreased muscle force production capacity (Horita, *et al.*, 2003; Horita, *et al.*, 1999; Kuitunen, *et al.*, 2002). Although these studies have greatly contributed to the understanding of the fatigue mechanisms involved in movements that simulate a vertical jump, less attention has been devoted to reveal possible changes in movement coordination. It is mainly because the movements performed in the sledge apparatus impose a significant constraint that limits the extension of the hip joint (i.e., leaning the trunk forward). This limitation may greatly affect jumping intersegmental coordination, as most of the work performed by the hip joint during countermovement jumps is devoted to accelerate the trunk upward (Bobbert & Van Soest, 1994). Moreover, the fatigue induced in the sledge apparatus has been investigated using either continuous or rebound jumps (Horita, *et al.*, 2003; Kuitunen, *et al.*, 2002; Rodacki, Fowler, & Bennett, 2001). However, it fails to mimic the intermittent condition observed in some sports (e.g., volleyball and basketball), in which there is an interval between subsequent vertical jumps.

A new method to investigate physiological and biomechanical effects of fatigue on vertical jump was recently developed (Pereira, *et al.*, 2011; Pereira, *et al.*, 2009a; Pereira, *et al.*, 2009b). This method has the advantage to allow vertical jump assessment close to real sports condition. Shortly, the individuals perform countermovement jumps intermittently at a fixed height (e.g., 95% of maximum vertical jump height) until fatigue (i.e., inability to sustain the target height for three consecutive jumps). Changes in the rest interval could postpone the fatigue, increasing the number of vertical jumps performed, and change the source of fatigue (Pereira, *et al.*, 2009b). Furthermore, this experimental approach allows for more realistic assessment of intersegmental vertical jump coordination as the intermittent unconstrained countermovement jumps do not neglect the contribution of the trunk segment as jumps performed in the sledge apparatus does.

It is reported that the restriction of ankle joint movement during vertical jumping increased the power and work output at the knee joint (Arakawa, Nagano, Hay, & Kanehisa, 2013). A large part of the enhanced output at the knee is assumed to be from ankle restriction, which results in the nullification of energy transportation via muscle gastrocnemius, i.e., reduced contribution of the energy transfer with ankle restriction appeared as augmentation at the knee joint. Then, as the number of intermittent vertical jumps progresses, the fatigue can decrease the muscle capability to generate force, leading to changes in joint contribution and intersegmental coordination. Alternatively, the maximal characteristic of the vertical jump may limit itself the coordination changes, while segmental contributions would change seeking to maintain the power output (i.e., jump height). Therefore, the aim of this study was to describe the intersegmental coordination and segmental contribution during intermittent vertical jumps performed until fatigue. It was hypothesized that exercise-induced fatigue would change vertical jump intersegmental coordination and segmental contribution of lower limbs.

Methods

Seven healthy male participants (mean ± SD; 23.9 ± 1.8 years; 74.5 ± 7.7 kg; 178 ± 6 cm), engaged in recreational volleyball practice, volunteered to participate in this study. Participants were asked to refrain from severe physical activity in the day before each experimental session. This study was previously approved by the Research Ethics Committee, which also provided the Ethical Guidelines followed in this study. Participants were informed about the procedures, benefits and risks before giving and signing the written informed consent.

Participants visited the laboratory on two occasions separated by a period of three days. In the first session, the maximum vertical jump height was determined followed by vertical jumps habituation. Participants performed five maximum vertical jumps with 1 minute resting interval between each jump. The maximum jump height was determined from the average of the five trials, because humans are able to achieve maximum power/strength in only 5% of their attempts. Thus, using 95% of the maximum jumping height as a target height during the fatigue protocol imposed a challenge to the participants that could be feasible (i.e., maintaining a given jumping height for a long period of time). The vertical jump habituation consisted of a set of jumps with a specific rest period length (6 s). This rest period length was chosen based on a previous study from our group (Pereira, *et al.*, 2009b). According to the number of vertical jumps in this session, the rest period length for each individual was determined (increased or decreased ~2 s) to ensure that participants would perform approximately 80 jumps. In the second session, participants were asked to perform intermittent countermovement jumps with a fixed rest interval individually determined (7.4 ± 1.6 s) with arms crossed in front of their chest to the target height set at 95% of their maximum jump height (Pereira, *et al.*, 2009b). Participants received visual feedback (on the monitor positioned in front of them) of their jump height immediately after each jump, which was estimated by impulse-moment method using customized LabView routine (National Instruments, Austin, Texas). Tests were halted when participants failed to reach the required height for three consecutive jumps. Kinematic and kinetic variables were recorded for all vertical jumps.

Infrared emitters were placed on the right side of each participant's body in the following sites: 1) lateral malleolus, 2) lateral femoral epicondyle of the knee, 3) the most prominent protuberance of the greater trochanter, and 4) acromion process. The optoelectric system (Optotrak 3020 – 3D Motion Measurement System, NDI) was used to record (200 Hz) the x, y and z coordinates of the IRED position and they were filtered using a zero lag, fourth order, and low pass digital Butterworth filter. Cut-off frequency was defined by residual analysis and set at 7 Hz (Winter, 2005). The coordinates of the joint points were used to calculate segment angular displacement of the shank, thigh and trunk (Figure 1).

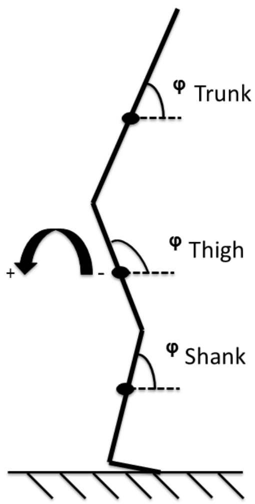

Figure 1. Convention used to define shank, thigh and trunk segmental angles (j).

A force platform (Kistler, model 9286A, Winterthur, Switzerland) was synchronized with the kinematic data measurements and sampled at 1000 Hz to provide force-time traces. The data were filtered using a zero lag, fourth order, and low pass digital Butterworth filter. Cut-off frequency was also defined by residual analysis and set at 13 Hz (Winter, 2005).

A custom MatlabTM routine was written to process and analyze the kinematic and kinetic data. The movement duration was defined from the beginning of eccentric phase to the takeoff instant. Movement duration was divided into two phases: the eccentric and concentric phase. The beginning of eccentric phase was defined as the instant when the vertical force decreased by 2% of body weight (eccentric phase beginning = body weight – (0.02·body weight)). Body weight was determined by averaging vertical force measured for 2 s during a quiet stance before the jumping protocol (Vanrenterghem, De Clercq, & Van Cleven, 2001). The end of the eccentric phase corresponded to the beginning of concentric phase and was defined as the instant in which the net velocity of the center of mass crossed zero after the unweighting phase (Bosco, & Komi, 1979). At this instant (movement reversal), body segment angles were determined. The end of concentric phase was determined when participants lost contact with the force platform (takeoff). The takeoff velocity consisted of the whole body velocity immediately before the takeoff, calculated from the net concentric impulse computed by using the impulse-momentum theorem (Linthorne, 2001). Jump height was calculated from the takeoff velocity using the equations of uniform accelerated motion.

A statistical tool known as principal component (PC) analysis (Daffertshofer, Lamoth, Meijer, & Beker, 2004) has been used to assess intersegmental coordination during movement performance. The PC analysis was already used in the investigation of intersegmental coordination in postural control (Freitas, Latash, & Duarte, 2006; Krishnamoorthy, Yang, & Scholz, 2005) and gait (Borghese, Bianchi, & Lacquaniti, 1996; Mah, Hulliger, Lee, & O'Callaghan, 1994). Therefore, intersegmental coordination (i.e., the relationship among body segments involved in the vertical jump) was assessed using PC analysis on the linear co-variation of sagittal plane shank, thigh and trunk segment angles from the beginning of the eccentric phase to the end of the concentric phase. The percentage of variance explained by each principal component (total of 3) and the contribution (PC loading factors) of shank, thigh, and trunk segment angles for each component were analyzed. The average of three vertical jumps performed in the beginning (from the fourth to the sixth jump), middle (the vertical jump at 50% position, and one jump before and after that) and end of the session (last three jumps) were considered for analysis to identify possible changes due to muscle fatigue.

After confirming the normality and homogeneity of variance (Shapiro-Wilk and Levene test, respectively), jumping height, vertical jump duration, and segment angle at movement reversal were compared between different instants (beginning, middle and end phases) with one-way repeated measures analyses of variance (ANOVAs). Additional one-way repeated measures ANOVA was employed to test the effect of fatigue (beginning, middle, and end) on the explained variance by the first PC, which explained more than 90% of the vertical jump segmental synergy. Finally, two-way repeated measures ANOVAs were carried out to test the effect of fatigue and segmental angle (shank, thigh, and trunk) on the loading factors (absolute Fisher *z*-transformed values) from the first PC. *Post-hoc* tests with Bonferroni corrections were used for multi-comparison purposes when necessary. Significance level was set at $p < .05$. Data are presented as mean ± SD.

Results

The vertical jump height decreased significantly from the beginning to the middle (-2.5%) and from the middle to the end of the test (-4.1%) (Figure 2A). The overall fall in vertical jump height (from the beginning to the end of the test) was -5.5% ($p < .001$). In addition, the vertical jump duration followed an inverse pattern of jump height, time increased significantly from the beginning to the middle (5.1%) and from the middle to the end (5.1%). The movement duration increased by 10.2% ($p < .001$) from the beginning to the end of the test (Figure 2B).

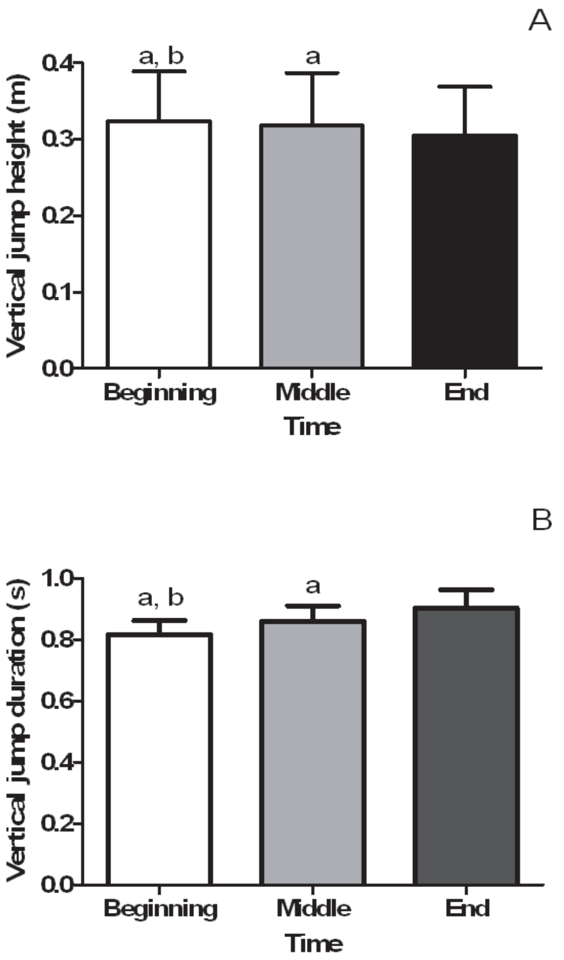

Figure 2. Vertical jump height (A) and duration (B) in different time. A: [a]different from the end ($p < .001$); [b]different from the middle ($p = .018$). B: [a]different from the end ($p = .04$); [b]different from the middle ($p = .03$).

Non-significant effect ($p = .09$) of fatigue on movement synergy was presented on the first PC (Figure 3A). In order to test the contribution of each segment movement to the first PC, a two-way repeated measure ANOVA (time to fatigue vs. segment) presented no interaction ($p = .40$) or time effect ($p = .60$), but presented an effect of segment on the loading factors ($p < .001$). *Post-hoc* tests showed that the thigh rotation contributed the most to the first PC, with the trunk second and the shank the least (Figure 3B).

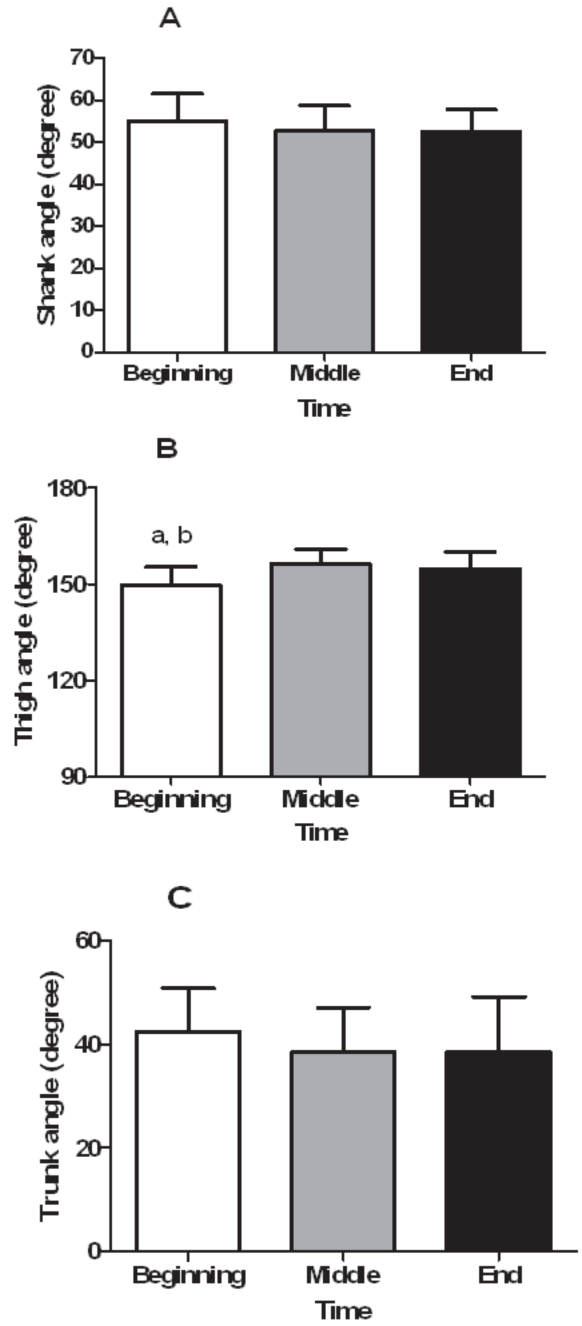

Figure 3. (A) Percentage of variance explained by the first principal component (PC1) for all instants (A). (B) It shows the contribution (loading) of each segment to the first PC. [a]different from thigh ($p < .01$); [b]different from trunk ($p < .001$).

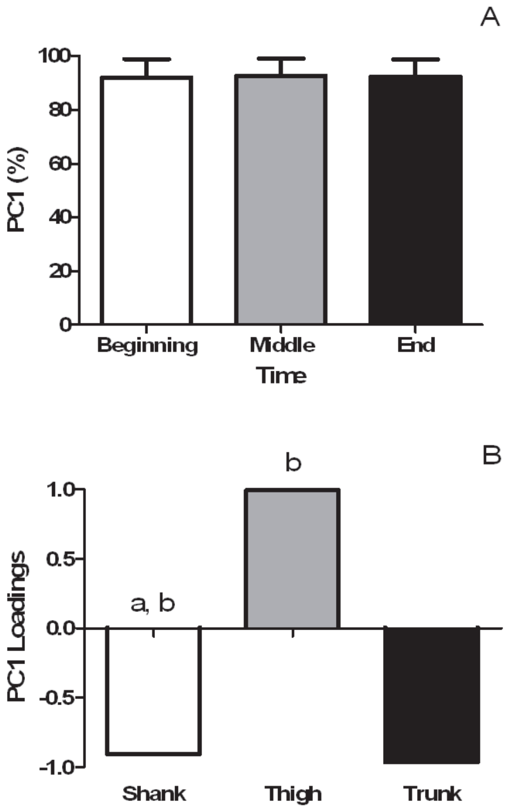

Figure 4. Segment angle at movement reversal in different time of shank (A), thigh (B) and trunk (C). [a]different from the end ($p < .001$); [b]different from the middle ($p < .001$).

The shank and trunk segment angles at movement reversal (transition from eccentric to concentric phase) did not differ significantly across the beginning (shank = 55°; trunk = 42°), middle (shank = 53°; trunk = 39°), and end instants (shank = 52°; trunk = 39°) ($p = .08$). However, the thigh segment angle at movement reversal was significantly increased (greater counterclockwise/backwards rotation) at the middle (4%) and end (4%) instants compared to the beginning instant (Figure 4).

Discussion

The aim of this study was to describe the intersegmental coordination and segment contributions during intermittent vertical jumps performed until fatigue. More than 90% of the intersegmental coordination was explained by one principal component, indicating that one movement synergy was responsible for the performance of the vertical jump during the process of fatigue. In addition, the segment contribution did not change during the fatigue process, with the thigh segment contributing the most and the shank segment the least to vertical jump.

In the present study, the fatigue protocol implied that jump performance (jump height) would decrease due to intermittent vertical jump repetitive execution. The average performance reduction (-5.5%) was similar to the one reported using similar exercise fatigue protocol (-6.7%) (Pereira, *et al.*, 2009a). However, it was smaller than the one reported after continuous vertical jump fatigue (-30%) (Rodacki, *et al.*, 2001), after knee extensors (-14%) (Rodacki, Fowler, & Bennett, 2002) and plantar flexors (-18%) (Bobbert, *et al.*, 2011) muscle fatigue. Thus, different vertical jump fatiguing protocols (intermittent *vs.* continuous exercise, isolated *vs.* whole muscle groups, or test interruption criterion) may explain such discrepancies in vertical jump performance reductions. Furthermore, the performance reductions in the present study are closer to game/training conditions of sports, based on the intermittency of our fatigue protocol. The vertical jump-induced fatigue protocol used in this study mimics the fatigue level reported by previous study, which described a reduced jump performance (-7.5%) when volleyball players performed intermittent volleyball attacks with resting period length similar to real match conditions (Pereira, *et al.*, 2008). Hence, the changes or conservations of movement synergies/contributions, which are approached below, may be considered closer to actual sports condition.

The vertical jump duration (i.e., summation of eccentric and concentric phases) increased significantly during the fatiguing protocol. It can be interpreted as movement adjustment to sustain the required target height (Hortobagyi, Lambert, & Kroll, 1991). The net impulse, mainly generated during concentric phase, is closely related to vertical velocity of center of mass at the takeoff, and this is related to the height achieved by center of mass during the flight phase. Therefore, the maintenance of jump height depends on the maintenance of net impulse. Since great amplitude of vertical ground reaction force has not been sustained under fatigue (Pereira, *et al.*, 2009a), a longer vertical jump duration was a strategy used to maintain the net impulse during fatigue, in order to maintain jump performance.

The increased vertical jump duration can also be a result of larger range of motion at the joints and/or increased joint reversal time (Hortobagyi, *et al.*, 1991). In the present study, the thigh segment angle at movement reversal increased significantly (greater counterclockwise rotation) as the exercise progressed, explaining the increased movement duration. However, muscle contractile impairments may also influence on movement duration (Rodacki, *et al.*, 2001). Such impairments have been reported on stretch-shortening cycle exercise-induced fatigue protocols performing simulated jumps (Horita, *et al.*, 2003; Ishikawa, *et al.*, 2006b) or real intermittent vertical jumps (Pereira, *et al.*, 2009b). In addition, the muscle stiffness and tendinous tissue compliance have changed after stretch-shortening cycle fatigue (Ishikawa, *et al.*, 2006a). The passive muscle stiffness usually increases after eccentric exercise (Ishikawa, *et al.*, 2006a) and it is determined by the non-contractile elements in the muscle, such as titin and desmin, which form elastic links between the thick filaments and Z-lines (Lieber, Thornel, & Friden, 1996). Thus, changes in the strain of these links after the exhausting stretch-shortening cycle fatigue exercises might lead to different passive tension slope during the exercise. Moreover, the concentric and isometric muscle function may be affected by the increased tendinous tissue compliance (Ishikawa, *et al.*, 2006a). Therefore, both greater counterclockwise rotations of the thigh and muscle contractile changes could explain the movement duration increases.

It has been reported that maximal voluntary isometric contraction of the quadriceps muscle decreases after using similar fatiguing protocol (Pereira, *et al.*, 2009b). Hence, one may expect that segment synergies would change during vertical jump-induced fatigue, in order to compensate the force reduction. However, the first principal component explained more than 90% of the vertical jump movement during the fatigue protocol. It means that an optimal intersegmental coordinative pattern was maintained from the beginning (non-fatigued condition) to the end (fatigued condition) of exercise, irrespective of muscle fatigue. Similar finding has been reported when fatigue was induced using continuous vertical jumps (Rodacki, *et al.*, 2001). Then, it suggests that the vertical jump performed closer to the maximum height (95%) has a specific/strict movement pattern that does not change under fatigue. This optimal solution could be built by practice and even during adverse conditions (e.g., fatigue) it could not be dramatically changed.

The segment contributions of vertical jump did not change during the intermittent vertical jump-induced fatigue protocol. The thigh rotation contributed the most to the first principal component, with the trunk second and the shank the least. It was hypothesized that segment contributions would change during fatigue, since the maximal voluntary isometric torque of the quadriceps muscle is reduced after similar fatigue protocol (Pereira, *et al.*, 2009b). One explanation for this result is that the jump height required in our study was very close to the maximum and the movement pattern was not changed to compensate the force loss. In addition, the constraint can reduce the movement degrees of freedom (Van Soest, & Van Galen, 1995). Then, as muscle fatigue is considered a constraint, the degrees of freedom of the vertical jump could reduce from two to one, decreasing drastically the possibility of changing the segment contributions and segmental synergies.

The results have some practical implications, which are: performing intermittent vertical jumps with approximately seven seconds between them can decrease the number of vertical jumps at fixed height. Fatigue does not change the segment contributions and segmental synergies, regardless of the reduction in jumping height. Implementing intermittent vertical jumps may be an alternative training paradigm to maintain jump height level during the session. However, the readers should consider the number of participants in this study, which hampers the external validity of our findings.

Conclusion

The same intersegmental coordination pattern is followed throughout the vertical jumps performed until fatigue. In addition, the contributions of the lower limb segments were maintained throughout the vertical jumps, while the thigh rotation contributed the most to jump height.

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Acknowledgements

CAPES and CNPq

Manuscript received on March 11, 2014
Manuscript accepted on August 5, 2014