

THE RELATIONSHIP BETWEEN VERTICAL STIFFNESS IN MAXIMAL AND SUB-MAXIMAL HOPPING TESTS AND RUNNING PERFORMANCE IN YOUNG MIDDLE-DISTANCE RUNNERS: A PILOT STUDY

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This study investigated the relationship between vertical stiffness in the sub-maximal and maximal bilateral hopping test and middle-distance running performance in young middle-distance runners. The longer distance running performance was more correlated with normalized vertical stiffness in sub-maximal hopping, while the sprint performance was statistically linked to vertical stiffness in maximal hopping. Vertical stiffness measured in combination of the sub-maximal and maximal hopping tests might be utilized as a useful indicator for middle-distance running performance. Accordingly, incorporating plyometric exercises, especially involving vertical motions, might benefit middle-distance running performance.

KEY WORDS: ATHLETICS, RUNNING ECONOMY, SPRING-MASS, DISTANCE RUNNING

INTRODUCTION: Generating and maintaining a high running speed, while making movements as economical as possible, is a key component of successful performances in middle-distance running. It has been well reported that there is a strong association between endurance running performance and running economy which is defined as the energy demand for a given speed of running (Saunders, Pyne, Telford, & Hawley, 2004). If improving running economy is related to improvements in distance running performance, investigating the factors that influence running economy would provide valuable information for performance enhancement. Mainly physiological and biomechanical factors are likely to influence running economy including but not limited to metabolic adaptations; the ability to store and release elastic energy during ground contact and push off, and efficient running mechanics that minimize energy waste (Foster & Lucia, 2007; Saunders et al., 2004).

The ability to store and release elastic energy during hopping or running activities is frequently described by a spring-mass model (Farley, Blickhan, Saito, & Taylor, 1991; McMahon & Cheng, 1990). The spring-mass model of the human body simply consists of a total body mass and a linear leg spring supporting the body mass. In this model, the leg behaves like a linear spring, the characteristics of the leg spring can be described by vertical stiffness. Vertical stiffness can be calculated as the ratio between vertical ground reaction force (GRF) and vertical displacement of the center of mass (CoM). There have been research studies examining the relationship between vertical/leg stiffness, running economy, and running performance. For example, it has been reported that the energy cost of running was highly related to the stiffness, at different running speeds, across different levels of runners (Dalleau, Belli, Bourdin, & Lacour, 1998; Dumke, Pfaffenroth, McBride, & McCauley, 2010; Heise & Martin, 1998). In addition, it has been demonstrated that vertical stiffness and running sprint performance influence each other mainly interact by running speed and stride frequency (Arampatzis, Brüggemann, & Metzler, 1999; Brughelli & Cronin, 2008; Farley & González, 1996).

Accordingly, vertical stiffness in hopping should show large correlations with the running performance of athletes. However, to our knowledge, the current literature lacks such evidence for the middle-distance running performance. Therefore, the aim of this study was to investigate the relationship between vertical stiffness in the sub-maximal and maximal bilateral hopping test and middle-distance running performance in young middle-distance runners.

METHODS: Six healthy adolescent male middle-distance runners participated in the test. They ranged in age from 14 to 16 years (15 ± 0.9 years), in height 156 to 181 cm (172.0 ± 9.7 cm), in body mass from 42.2 to 62.9 kg (53.8 ± 8.9 kg), and in leg length (the distance between the greater trochanter and the ground measured in upright stance) from 77.0 to 89.7 cm (82.7 ± 5.3 cm). Regular testing protocol consists of multiple testing days in a week, including the bilateral vertical hopping tests (sub-maximal in 2.2 Hz & maximal height in self-selected frequency), 300m sprint, 600m, 1000m, and 3000m running time trials. Every runner participated in one or two testing sessions. Each test and time trial was conducted at the same time of a day for each participant.

The repeated hopping tests were performed on a dual force plate system (Kistler 9286, Kistler Instruments, Winterhur, Switzerland). Kinetic data was sampled at 1000 Hz. Before the hopping test, all participants were instructed to place their hands placed on their hips, keep their knees straight and land in a similar position to that of take-off from the force plates and minimize ground contact times as possible, which minimize secondary movements in knee and hip joints. Participants performed a series of 40 consecutive bilateral hops for the sub-maximal hopping test. Hopping frequency was provided with a digital metronome in visual and auditory signals. For the maximal hopping test, participant performed a series of 10 maximal height hops. If the participant failed to perform the hopping trial adequately, the trial was disregarded and repeated after two minutes of rest. Time trials were conducted on a 200 m indoor tartan track. Each race duration was captured by the magnetic timing system (Freelap SA, Fleurier, Switzerland).

GRF time series were filtered at 12 Hz with a zero phase-lag fourth-order low-pass Butterworth filter. Individual hops were determined based on a contact period (vertical GRF above 10 N). Ten and six consecutive hops were used and averaged for the analysis for the sub-maximal and maximal hopping test respectively. Hopping frequency, ground contact time, and aerial time were calculated from vertical component of GRF. Vertical stiffness (K_{vert}) was calculated as:

$$K_{\text{vert}} = F_{\text{max}}/\Delta\text{CoM}$$

where F_{max} is the peak vertical GRF and ΔCoM is maximum vertical displacement of the CoM, which was calculated by integrating the vertical acceleration twice with respect to time. The initial velocity of the first integration was estimated by the aerial time of the previous hop (Hobara, Kobayashi, Yoshida, & Mochimaru, 2015). K_{vert} was normalized relative to body weight and leg length since body size influence K_{vert} (McMahon & Cheng, 1990). All calculations were processed using custom written Matlab program (Mathworks, Version 8.4). Pairwise correlations between hopping variables and the race duration were examined using Person correlation coefficients (r). Magnitudes of r were interpreted using thresholds of .1, .3, .5, and .7 for small, moderate, large, and very large correlations, respectively.

RESULTS AND DISCUSSION: Table 1 summarizes correlations between hopping parameters and the running performance. K_{vert} in the sub-maximal and maximal hopping tests exhibited large correlations with the running performance across the different distances. K_{vert} and normalized K_{vert} during the sub-maximal hopping test exhibited the largest correlation with the 3000m running performance. On the other hand, K_{vert} and normalized K_{vert} during the maximal hopping test exhibited the largest correlation with the 300 m sprint performance.

The main results of this study indicate that the longer distance running performance is more correlated with normalized K_{vert} in sub-maximal hopping, while the 300m sprint performance is statistically linked to the normalized K_{vert} in maximal hopping. The first finding may suggest that an increase in the stiffness of the lower body, specifically in higher hopping frequency appears to improve longer distance running performance by improving running economy. This

finding is consistent with studies that reported decreases in K_{vert} during prolonged or exhausting treadmill runs at a constant velocity or self-paced field races (Dutto & Smith, 2002; Hunter & Smith, 2007). On the other hand, stiffness in the maximal hopping test seems more representative of the ability to maintain speed over a shorter distance. Indeed, Hobara et al. (2009) showed that the knee stiffness is the major determinant of leg stiffness during maximal hopping and the mechanism is kinematically similar to the drop jump. Overall, these findings suggest that the vertical stiffness measured in combination of the sub-maximal and maximal hopping tests might be utilized as a useful indicator for middle-distance running performance since middle-distance races are faced with a unique challenge to generate high running speeds while making movements as economical as possible.

CONCLUSION: Vertical stiffness measures in the sub-maximal and maximal hopping test were correlated with sprinting and running performance, indicating a benefit of lower-body hopping testing and training in middle-distance running. Accordingly, incorporating plyometric exercises, especially involving vertical motions, might benefit middle-distance running performance since plyometric actions rely on stretch-shortening-cycle utilization and the rapid development of high forces.

Table 1
Intercorrelation matrix between hopping parameters and the performance of running

Running Distance	Sub-maximal Hopping			Maximal Hopping		
	K_{vert}	Normalized K_{vert}	Reactive Index	K_{vert}	Normalized K_{vert}	Reactive Index
300m	-.63*	-.36	-.04	-.80*	-.70*	-.67*
600m	-.66*	-.45	-.31	-.68*	-.56	-.48
1000m	-.57*	-.37	-.14	-.61*	-.44	-.42
3000m	-.72*	-.75*	-.48	-.49	-.45	-.68*

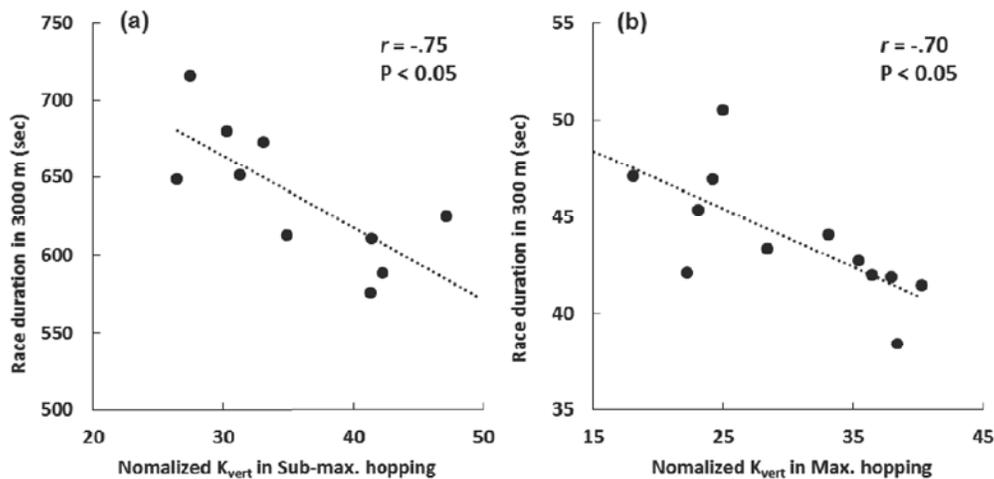


Figure 1: Linear relationship between (a) dimensionless K_{vert} in 2.2 Hz hopping and duration in 3000m race and (b) dimensionless K_{vert} in maximal hopping and race duration in 300m race

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