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**Vertical stiffness during one-legged hopping with and without using a
running-specific prosthesis**

Hiroaki Hobara,^{1*} Satoru Hashizume,¹ Johannes Funken,² Steffen Willwacher,^{2,3}
Ralf Müller,² Alena M. Grabowski,^{4,5} Wolfgang Potthast,^{2,6}

¹National Institute of Advanced Industrial Science & Technology (AIST), Tokyo, Japan

²German Sport University Cologne, Cologne, Germany

³Institute of Functional Diagnostics, Cologne, Germany

⁴Integrative Physiology Department, University of Colorado Boulder, CO, USA

⁵Eastern Colorado Healthcare System, Department of Veterans Affairs, Denver, CO, USA

⁶ARCUS Clinics Pforzheim, Pforzheim, Germany

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Correspondence address;

Hiroaki Hobara, Ph.D.

Artificial Intelligence Research Center,

National Institute of Advanced Industrial Science & Technology

AIST Tokyo Waterfront 3F, 2-3-26,

Aomi, Koto-ku, Tokyo 135-0064, Japan

TEL: +81-3-3599-8201

FAX: +81-3-5500-5233

E-mail: hobara-hiroaki@aist.go.jp

Abstract

Although athletes with unilateral below-the-knee amputations (BKAs) generally use their affected leg, including their prosthesis, as their take-off leg for the long jump, little is known about the spring-like leg behavior and stiffness regulation of the affected leg. The purpose of this study was to investigate vertical stiffness during one-legged hopping in an elite-level long jump athlete with a unilateral BKA. We used the spring-mass model to calculate vertical stiffness, which equals the ratio of maximum vertical ground reaction force to maximum center of mass displacement, while the athlete with a BKA hopped on one leg at a range of frequencies. Then, we compared the vertical stiffness of this athlete to seven non-amputee elite-level long-jumpers. We found that from 1.8 to 3.4 Hz, the vertical stiffness of the unaffected leg for an athlete with a BKA increases with faster hopping frequencies, but the vertical stiffness of the affected leg remains nearly constant across frequencies. The athlete with a BKA attained the desired hopping frequencies at 2.2 and 2.6 Hz, but was unable to match the lowest (1.8 Hz) and two highest frequencies (3.0 and 3.4 Hz) using his affected leg. We also found that at 2.5 Hz, unaffected leg vertical stiffness was 15% greater than affected leg vertical stiffness, and the vertical stiffness of non-amputee long-jumpers was 32% greater than the affected leg vertical stiffness of an athlete with a BKA. The results of the present study suggest that the vertical stiffness regulation strategy of an athlete with a unilateral BKA is not the same in the unaffected versus affected legs, and compared to non-amputees.

Keywords: spring-mass model; amputees; locomotion; long jump

1. Introduction

During bouncing gaits such as hopping, running, and jumping, human biological legs exhibit mechanical characteristics similar to those of a spring. Vertical stiffness (k_{vert}), defined as the ratio of peak vertical ground reaction force to maximum vertical center of mass (COM) displacement (Blickhan, 1989), is adjusted to accommodate the task demands. For example, previous studies have demonstrated that k_{vert} increases with faster hopping frequencies (Farley et al., 1991; Hobara et al., 2010a and 2013) and with hopping height at a given hopping frequency (Arampatzis et al., 2001; Farley et al., 1991; Hobara et al., 2007). Further, some cross-sectional studies suggest that endurance training enhances k_{vert} , but strength training, including weight training and/or plyometrics, has a stronger influence on k_{vert} than endurance training (Girard et al., 2010; Harrison et al., 2004; Hobara et al., 2008, 2010b; Laffaye et al., 2005; Rabita et al., 2008). Further, leg spring stiffness and an optimal angle of attack likely influence long jump performance (Seyfarth et al., 1999). Spring-like leg behavior and stiffness regulation have long been considered the principal characteristics of bouncing gaits for legged animals including humans, but it is still unknown how individuals with a lower extremity amputation who use a running-specific prosthesis regulate their spring-like leg behavior during bouncing gaits. A better understanding of spring-like leg behavior and stiffness regulation in this population will provide us with insight into the underlying biomechanics and control mechanism in humans and would be expected to aid in developing design parameters for spring-based prostheses for running (Farley and Gonzalez, 1996).

The use of carbon fiber running-specific prostheses (RSPs) have allowed individuals with lower extremity amputations to compete at elite levels (Hobara et al., 2015; Weyand et al., 2009; Willwacher et al., 2017). One athlete with a transtibial amputation has achieved long jump distances that are competitive in non-amputee sanctioned events (Willwacher et al., 2017). Previous studies have shown that an athlete with bilateral transtibial amputations who uses RSPs and has a 400 m time equivalent to non-amputees, achieves similar sprint speeds using different biomechanics (Brüggemann et al., 2009; Weyand et al., 2009). Further, a recent finding indicates that elite-level long-jumpers with unilateral transtibial amputations who use RSPs utilize different biomechanics during the run-up and take-off step of the long jump compared to performance-matched non-amputee long-jumpers (Willwacher et al., 2017). Although the affected leg including an RSP is typically used as the take-off leg in current Paralympic long jump events (Nolan et al., 2011 and 2012), little is known about the spring-like leg behavior and leg stiffness regulation of elite-level long-jumpers with unilateral transtibial amputations who use an RSP.

The purpose of this study was to investigate k_{vert} during hopping in an elite-level long-jump athlete with a unilateral below-the-knee (transtibial) amputation (BKA) across frequencies and to compare k_{vert} to non-amputee long-jumpers at one hopping frequency. According to a previous study, athletes with a unilateral BKA using an RSP could alter their unaffected k_{vert} to regulate step frequency during running at a given speed, but not prosthetic k_{vert} (Oudenhoven et al., 2017; McGowan et al., 2012). Hence, we hypothesized that an athlete with a BKA would not be able to hop on his affected leg at slow and fast hopping frequencies because k_{vert} cannot be changed. We also hypothesized that an elite

long-jumper with a BKA and superior long jump performance compared to non-amputee long jumpers would have greater k_{vert} in both legs compared to non-amputees during single leg hopping.

2. Methods

2.1 Participants

In experiment 1, one elite athlete with a unilateral below-the-knee amputation (BKA; male, age: 27 years; body mass including socket and prosthesis: 76.16 kg; standing height: 1.85 m; time since amputation: 13 years; long-jump personal best record [PR]: 8.40 m; training frequency: 6 days per week [2 days for strength training and 4 days for athletic specific training]) participated in the study. In experiment 2, seven non-amputee (NA) male long-jumpers who were competitive at international, national and regional levels participated. The participants' physical characteristics were the following: age 24.6 ± 2.5 years; standing height 1.82 ± 0.07 m; body mass 80.1 ± 6.22 kg; PR 7.64 ± 0.65 m (mean \pm SD); training frequency: 6 days per week [1-2 days for strength training and 4-5 days for athletic specific training]. In previous long jump events, the athlete with a BKA used his affected leg as his take-off leg. The protocol was approved by the local ethical committee and was in accordance with the guidelines set out in the Declaration of Helsinki (1983).

2.2 Task and procedure

In experiment 1, the athlete with a BKA was asked to hop in place on one leg with his hands on his hips. He hopped on a force plate (60 cm \times 40 cm, P400600-10000PT, AMTI, Watertown, MA, USA) while we recorded vertical ground reaction forces (vGRF) at 2000

Hz. He was asked to hop to the beat of an audible digital metronome on his unaffected leg and on his affected leg at 1.8, 2.2, 2.6, 3.0 and 3.4 Hz. Hopping frequencies that span the range of 1.8 and 3.4 Hz represent the broadest possible range for the subject (unaffected leg) to follow the metronome beat. Since instructions about contact time can affect stiffness regulation during hopping at a given hopping frequency (Arampatzis et al., 2001; Farley et al., 1991; Hobara et al., 2007), we asked subjects to hop with as short of a contact time as possible. Prior to data collection, subjects were given as much time as needed to practice hopping at each frequency. The athlete with a BKA hopped at five frequencies for each leg in a random order with a five-minute rest period between trials. The athlete with a BKA wore his competition running-specific prosthesis (stiffness category 7 Cheetah Xtreme; Össur, Reykjavik, Iceland), that included a customized rubber sole.

In experiment 2, both NAs and the athlete with a BKA were asked to hop in place on one leg at 2.5 Hz (Jia and Smith, 2001) with their hands on their hips. Subjects hopped on a force plate (60 cm × 40 cm, Kistler Instrumente AG, Winterthur, Switzerland) while we recorded vGRF at 1000 Hz. All participants hopped at 2.5 Hz on their non-take-off leg (unaffected leg for the athlete with a BKA) and take-off leg (affected leg for the athlete with a BKA) in a random order. Since experiments 1 and 2 were performed at different institutions, we used different hardware and sampling frequencies.

2.3 Data collection and analysis

In both Experiments 1 and 2, we collected data from 15 consecutive hops and used hops 6-10 for data analysis. The actual hopping frequency, ground contact time and aerial time

were determined using vGRF. The timing of foot-ground contact was determined using a 10 N threshold of vGRF.

According to a previous study (Blickhan, 1989), we calculated k_{vert} utilizing peak vGRF and maximum vertical COM displacement (ΔCOM) from the spring-mass model (Figure 1-A and B) (Eqn. 1).

$$k_{\text{vert}} = F_{\text{peak}} / \Delta\text{COM} \quad (1)$$

where F_{peak} is peak vGRF in N, and ΔCOM is maximum vertical COM displacement in m, respectively. In the present study, ΔCOM was obtained by integrating the vertical acceleration twice (Eqn. 2).

$$\Delta\text{COM}(t) = \int \int \frac{F(t) - mg}{m} dt \, dt \quad (2)$$

where F is the vGRF, m is the body mass, and g is the gravitational acceleration. The initial value of first integral (v_0) was obtained using equation 3:

$$v_0 = -0.5gt_a \quad (3)$$

where t_a is the aerial time. Since body size presumably influences stiffness (Farley et al., 1993), we divided k_{vert} by body mass, which included the prosthesis for the athlete with a BKA.

2.4 Statistics

In experiment 1, we analyzed hops that were within 5% of the designated metronome frequency (Granata et al., 2002; Padua et al., 2005). Further, we performed linear regression analyses for each spring-mass parameter (k_{vert} , F_{peak} , ΔCOM and contact time) for each of the five hopping frequencies. Bilateral differences (%) between legs were calculated for k_{vert} , F_{peak} , ΔCOM and contact time, as described previously (Watsford et al., 2010). In experiment 2, we used a series of one-sample *t*-tests to determine whether k_{vert} and the spring-mass parameters in NAs were statistically different from those of the athlete with a BKA. Statistical significance was set at $p < 0.05$. Statistical analysis was executed using SPSS (IBM SPSS Statistics Version 19, SPSS Inc., Chicago, IL, USA).

3. Results

3.1 Experiment 1

The athlete with a BKA was able to match the metronome frequency within 5% for all hopping frequencies with his non-take-off (unaffected) leg (Table 1). However, although the athlete with a BKA could match the designated metronome frequency at 2.2 and 2.6 Hz within 5% using his take-off (affected) leg, he was not able to match the slowest (1.8 Hz) and two fastest frequencies (3.0 and 3.4 Hz).

The non-take-off (unaffected) and take-off (affected) leg of the athlete with a BKA were compressed during the first half of ground contact, and vGRF increased with COM displacement (Fig. 2). In the non-take-off (unaffected) leg, there was a positive linear relationship between hopping frequency and k_{vert} ($R^2=0.95$, $p < 0.01$). However, in the

take-off (affected) leg, there was not a significant linear relationship between hopping frequency and k_{vert} ($R^2=0.79$, $p=0.11$). From 1.8 to 3.4 Hz, k_{vert} of the non-take-off (unaffected) leg increased by 54% (Figure 3-A). From 2.2 to 2.6 Hz, k_{vert} of the non-take-off (unaffected) leg increased by 19.8%, but k_{vert} of the take-off (affected) leg only increased by 2.1% (Figure 3-A). Consequently, the bilateral difference in k_{vert} between the non-take-off (unaffected) and take-off (affected) leg was 55.9% and 90.3% during hopping at 2.2 and 2.6 Hz, respectively.

From 1.8 to 3.4 Hz, there was a negative linear relationship between hopping frequency and F_{peak} for the non-take-off (unaffected) leg ($R^2=-0.96$, $p < 0.01$), where F_{peak} decreased by 46% across frequencies (Figure 3-B). We also found a negative linear relationship between hopping frequency and F_{peak} for the take-off (affected) leg ($R^2=-0.90$, $p < 0.05$). From 2.2 to 2.6 Hz, F_{peak} decreased by 10.4% in the non-take-off (unaffected) leg, but decreased by 31.4% in the take-off (affected) leg (Figure 3-B). We also found that the bilateral difference in F_{peak} between legs was 30.5% and 55.3% during hopping at 2.2 and 2.6 Hz, respectively.

There was a negative linear relationship between hopping frequency and ΔCOM for the non-take-off (unaffected) leg ($R^2=-0.82$, $p < 0.05$), where ΔCOM decreased by 35% from 1.8 to 3.4 Hz (Figure 3-C). We also found a negative linear relationship between hopping frequency and ΔCOM for the take-off (affected) leg ($R^2=-0.93$, $p < 0.05$), where ΔCOM decreased by 47% from 1.96 to 2.82 Hz (Figure 3-C). From 2.2 to 2.6 Hz, ΔCOM decreased by 37.7% and 34.3% in the non-take-off (unaffected) and take-off (affected) leg, respectively (Figure 3-C). Bilateral differences in ΔCOM between legs were 16.3% and 18.4% during hopping at 2.2 and 2.6 Hz, respectively. There were no significant

relationships between hopping frequency and contact time in the non-take-off (unaffected) and take-off (affected) leg, respectively. (Figure 3-D). Contact times for the take-off (affected) leg were 23.2% and 32.8% longer than those of the non-take-off (unaffected) leg at 2.2 and 2.6 Hz, respectively (Figure 3-D).

3.2 Experiment 2

We found that k_{vert} of the non-take-off (unaffected) leg in the athlete with a BKA was 15% greater than that of the non-take-off leg in NAs ($t_{(6)} = -5.91, p < 0.01$; Figure 4-A). However, k_{vert} of the take-off (affected) leg in the athlete with a BKA was 33% lower than that of the take-off leg in NAs ($t_{(6)} = 5.05, p < 0.01$; Figure 4-A). Although the peak vGRF of the take-off (affected) leg in the athlete with a BKA was significantly lower than that of the take-off leg in NAs ($t_{(6)} = 4.73, p < 0.01$), there were no significant differences in peak vGRF between the non-take-off (unaffected) leg in the athlete with a BKA and the non-take-off leg in NAs ($t_{(6)} = -1.63, p = 0.15$; Figure 4-B). We found that the COM displacement for the non-take-off (unaffected) leg and take-off (affected) leg were significantly smaller ($t_{(6)} = 6.45, p < 0.01$) and larger ($t_{(6)} = -5.64, p < 0.01$) in the athlete with a BKA than in NAs, respectively (Figure 4-C). Contact time of the non-take-off (unaffected) leg in the athlete with a BKA was significantly shorter than that of the non-take-off leg in NAs ($t_{(6)} = 4.16, p < 0.01$; Figure 4-D). On the other hand, there were no significant differences in contact time between the take-off (affected) leg in the athlete with a BKA and the take-off leg in NAs ($t_{(6)} = 0.52, p = 0.62$; Figure 4-D).

4. Discussion

The purpose of this study was to investigate k_{vert} during hopping in an elite-level long-jump athlete with a unilateral BKA across frequencies and to compare k_{vert} to non-amputee long-jumpers at one hopping frequency. We found that k_{vert} increased with faster hopping frequencies when the athlete with a BKA hopped using his non-take-off (unaffected) leg (Figure 3-A). These results are in agreement with previous studies that have shown that k_{vert} increases with faster hopping frequencies (Farley et al., 1991; Hobara et al., 2010a and 2013). However, the athlete with a BKA could not match the slowest (1.8 Hz) and two fastest hopping frequencies (3.0 and 3.4 Hz) with his affected leg, and k_{vert} of the take-off (affected) leg remained nearly constant over a wide range of hopping frequencies (Figure 3-A). These results support our initial hypothesis that an athlete with a BKA would not be able to hop at slower and faster hopping frequencies with his affected leg, which includes an RSP because the stiffness of the RSP remains nearly constant. Therefore, these results indicate that use of a running-specific prosthesis in an athlete with a BKA only allows vertical stiffness control within a narrow range of hopping frequencies compared to the non-take-off (affected) leg. Thus, the stiffness of the running-specific prosthesis likely dictates vertical stiffness during hopping, similar to running (Beck et al. 2017).

Overall, for all measured hopping frequencies, k_{vert} was greater in the non-take-off (unaffected) leg compared to the take-off (affected) leg (Figure 3-A). These results agree with previous studies that leg and vertical stiffness in the affected leg are lower than in the unaffected leg during running and sprinting in athletes with unilateral transtibial amputations (Hobara et al., 2013; Grabowski et al 2010; McGowan et al 2012) and during

sprinting in athletes with unilateral transfemoral amputations (Sano et al., 2017) using running-specific prostheses (RSPs). We also found that the lower k_{vert} in the take-off (affected) leg compared to the non-take-off (unaffected) leg was due to a smaller peak vGRF and greater COM displacement at all hopping frequencies (Figure 3-B and C). Several studies have demonstrated that GRFs of the affected leg of sprinters with an amputation using RSPs are lower than those of the unaffected leg during running and sprinting (Brüggemann et al., 2009; Grabowski et al., 2010; Hobara et al., 2013; McGowan et al., 2012; Weyand et al., 2009). Previous studies suggest that each RSP has different inertial properties (Baum et al., 2013), and the dynamic elastic response of RSPs (Brüggemann et al., 2009; Noroozi et al., 2014; Beck et al 2016) is different from that of the biological legs of non-amputees. In addition, Isakov et al. (1996) found muscle atrophy and reduced strength in the quadriceps and hamstrings of the affected leg after amputation (13.4 ± 14.4 years, mean \pm SD). Therefore, the present study and previous findings suggest that the RSP's mechanical properties and/or muscle weakness/impairment due to atrophy after amputation could limit force production capability and thus affect vertical stiffness.

In experiment 2, we found that k_{vert} of the take-off (affected) leg of the athlete with a BKA was significantly lower than that of NAs (Figure 4-A) and k_{vert} of the non-take-off (unaffected) leg of the athlete with a BKA was significantly greater than that of NAs.

These results partly support our second hypothesis that an athlete with a BKA with superior long jump performance compared to the average of non-amputee long jumpers would have greater k_{vert} in both legs during hopping. As shown in Figure 4-B and C, the lower k_{vert} of the take-off (affected) leg in the athlete with a BKA compared to NAs was

due to a smaller peak vGRF and greater COM displacement. As noted above, the mechanical properties of RSPs and/or muscle weakness/impairment due to atrophy after amputation could limit force production capability, and lead to lower k_{vert} in the affected leg of the athlete with a BKA compared to NAs.

We found that k_{vert} of the non-take-off leg (unaffected leg) in the athlete with a BKA was significantly greater than that of NAs (Figure 4-A). Some cross-sectional studies indicate that long-term physical training and adaptation modify k_{vert} . For example, past findings imply that endurance training enhances k_{vert} (Girard et al., 2010; Hobara et al., 2010b), but that plyometric training has a stronger influence on k_{vert} than endurance training (Harrison et al., 2004; Hobara et al., 2008; Laffaye et al., 2005; Rabita et al., 2008). Further, leg stiffness depends on the combination of the individual stiffness values of muscles and tendons (Butler et al., 2003). Although Sherk et al. (2010) did not take into account training history and/or intensity, they reported that muscle cross-sectional areas of the intact lower extremities of people with transtibial amputations were similar to those of age- and sex-matched non-amputee control groups. Therefore, the present study and past findings suggest that greater k_{vert} of the non-take-off (unaffected) leg in an athlete with a BKA compared to NAs may be due to long-term adaptations for muscle stiffness and/or tendon stiffness through daily physical training.

There were some potential limitations of the current study. First, due to the limited number of athletes with a BKA who have achieved long jump distances that are competitive with non-amputees, we only recruited one athlete with a BKA. However, according to an *a priori* power analysis, 20 participants for both groups would allow adequate statistical power. As described in previous literature (Keogh, 2011), the small

number of participants with a disability limits the statistical power of the study, which should be considered when interpreting our results and generalizing our findings. To determine the stiffness regulation in the athletes with a BKA and understand the biomechanics resulting from the use of RSPs, more subjects should be recruited in future research. Second, although we found differences in stiffness regulation between one athlete with a BKA and seven non-amputees, there may be confounding influences of training history/load and competition levels. Further, there may be a potential compensation effect by the unaffected leg due to the inability of the affected leg to neurally modulate stiffness. Therefore, these factors should be considered when interpreting our results. Thirdly, vertical stiffness depends on joint stiffness, which can be modulated by neuromuscular control, joint angle, and the stiffness of muscles and tendons (Butler et al., 2003; Farley et al., 1998; Hobara et al., 2007). Additional research is needed to determine the underlying mechanisms responsible for the different vertical stiffness regulation strategies in the affected and unaffected legs of athletes with a BKA. Finally, k_{vert} of the take-off (affected) leg of the athlete with a BKA was significantly lower than that of NAs. In a previous study, using a simple spring-mass model, Seyfarth et al. (1999) suggested that there is a minimum leg stiffness that optimizes long jump performance and further increasing stiffness does not lead to longer jumps. However, previous studies have shown that k_{vert} is correlated with agility and speed during sprint running in NAs (Bret et al., 2002; Chelly and Denis, 2001; Durand et al., 2010). Therefore, our results indicate that there are differences between NAs and athlete with a BKA in their regulation of k_{vert} , which may potentially affect long jump performance. Further, k_{vert} of the take-off (affected) leg during one-legged hopping may not predict long jump performance in

athletes with a BKA. The contributions of the motor control strategy and the inherent mechanical properties of an RSP to long jump performance remain to be investigated.

5. Conclusion

The purpose of this study was to investigate vertical stiffness (k_{vert}) during hopping in an athlete with a unilateral below-the-knee amputation (BKA). Over a wide range of hopping frequencies, k_{vert} of the non-take-off (unaffected) leg increases with faster hopping frequencies, but k_{vert} of the take-off (affected) leg remains nearly constant in this athlete, presumably due to the set stiffness of the running-specific prosthesis and/or the stiffness of the remaining muscles and tendons in the residual limb. We also found that k_{vert} of the non-take-off (unaffected) leg in an athlete with a BKA was greater than that of non-amputees, but k_{vert} of the take-off (affected) leg in an athlete with a BKA was lower than that of non-amputees. The results of the present study suggest that the vertical stiffness regulation strategy adopted by athletes with BKAs is not the same between their unaffected and affected legs, and this strategy is different from that of non-amputees with inferior long-jump performance and different training regimes.

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Conflict of interest

None of the authors have any conflicts of interest associated with this study.

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Figure legends

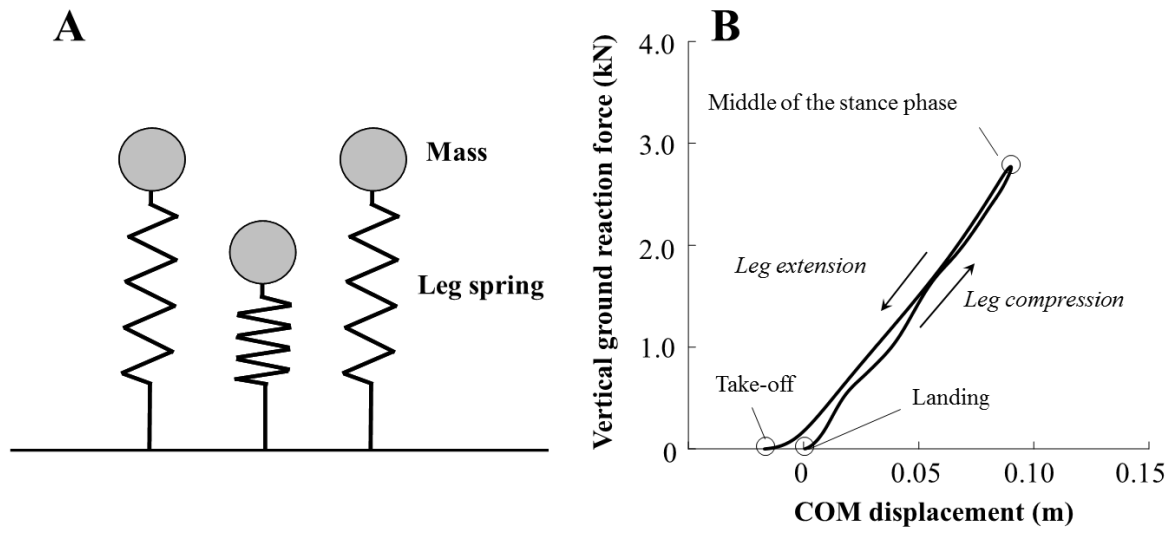
Figure 1. A: Spring-mass model for hopping. This model consists of a point mass that represents body mass and a leg comprised of a massless linear spring supporting the body mass. The model is shown at the beginning of the ground contact phase (*left*), the middle of the ground contact phase (*middle*), and at the end of the ground contact phase (*right*). B: An example of vertical ground reaction force (vGRF) versus center of mass (COM) displacement from the unaffected leg of an athlete with a below-the-knee amputation (BKA) hopping at 2.2 Hz. The leg is compressed from the instant of touchdown, and vGRF increases. The vGRF is highest at mid-stance, and subsequently decreases as the leg extends until take-off. Vertical stiffness is calculated from the peak vGRF divided by the maximum COM displacement.

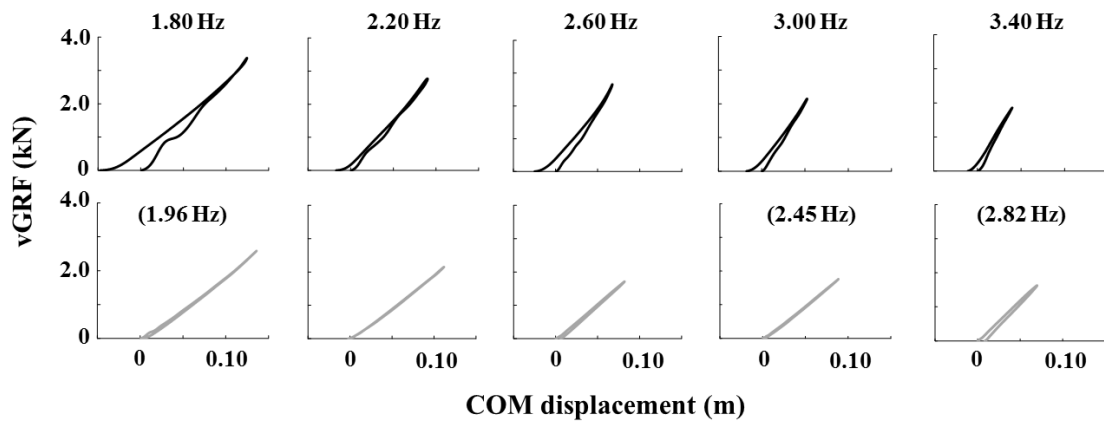
Figure 2. Typical examples of vertical ground reaction force (vGRF) versus center of mass (COM) displacement from an athlete with a BKA at five hopping frequencies. Black (top graphs) and gray (bottom graphs) lines represent the non-take-off (unaffected) leg and take-off (affected) leg, respectively. Vertical stiffness is calculated from the peak vGRF divided by the maximum COM displacement. Numbers within parentheses indicate the actual hopping frequency recorded from the take-off (affected) leg (see Table 1).

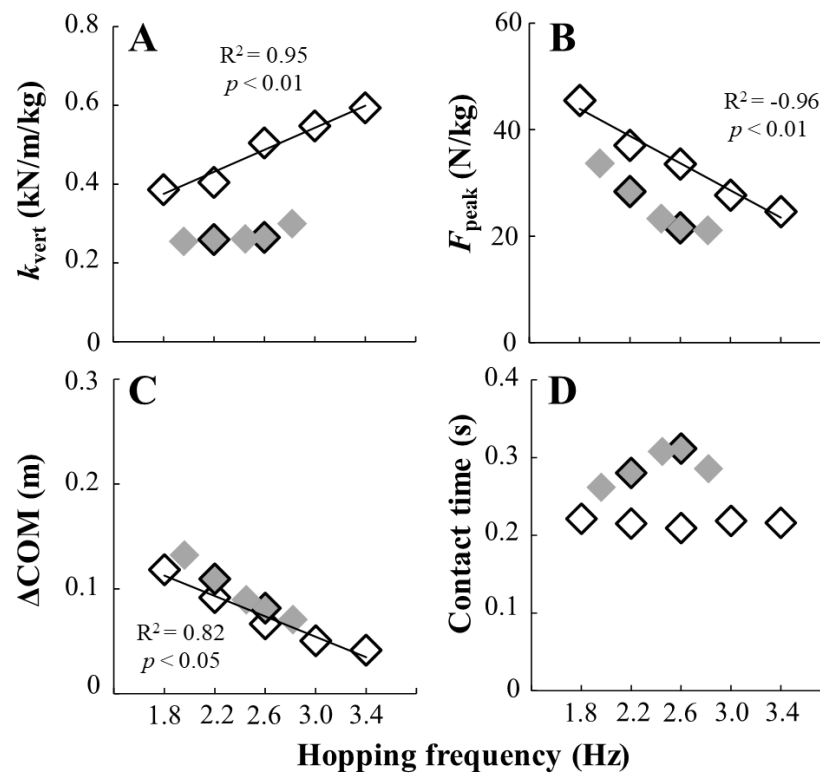
Figure 3. A: Vertical stiffness, B: peak vGRF, C: Δ COM and D: ground contact time in an athlete with a BKA across five hopping frequencies. White and gray symbols represent the non-take-off (unaffected) leg and take-off (affected) leg, respectively. Symbols with no outline indicate that the athlete with a BKA could not match the slowest (1.8 Hz) and two fastest frequencies (3.0 and 3.4 Hz) within 5% using his take-off (affected) leg.

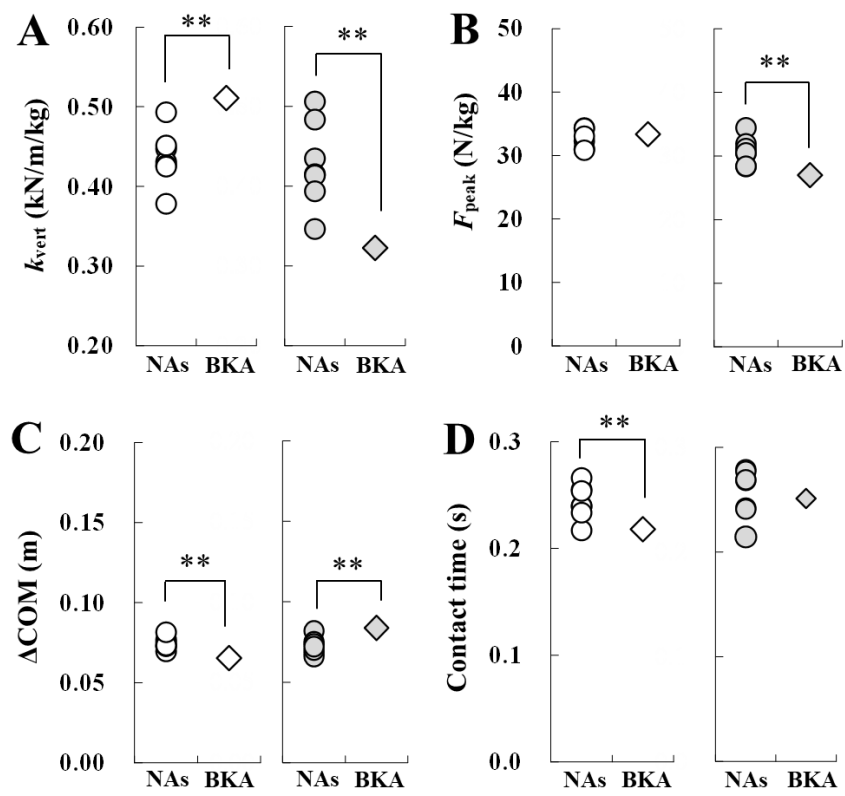
Figure 4. Comparison of A: vertical stiffness (k_{vert}), B: peak vertical ground reaction force (vGRF), C: change in center of mass displacement (Δ COM) and D: ground contact time between non-amputee long jumpers (NAs) and an elite-level long-jump athlete with a BKA during hopping at 2.5 Hz. Open symbols and grey symbols represent the non-take-off (unaffected) leg and take-off (affected) leg, respectively. The asterisks (**) indicate a significant difference at $p < 0.01$.

Table 1. Actual hopping frequencies for the non-take-off (unaffected) and take-off (affected) legs of an athlete with a BKA. Bold number indicates that the athlete with a BKA was not within 5% of the designated metronome frequency.









Graphical abstract

	Actual hopping frequency (Hz)				
Non take-off (Unaffected)	1.80 (0.05)	2.21 (0.03)	2.59 (0.04)	3.00 (0.06)	3.37 (0.10)
Take-off (Affected)	1.96 (0.02)	2.18 (0.03)	2.57 (0.03)	2.45 (0.02)	2.82 (0.10)