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INDIVIDUAL HOP ANALYSIS AND REACTIVE STRENGTH RATIOS PROVIDE BETTER DISCRIMINATION OF ACL RECONSTRUCTED LIMB DEFICITS THAN TRIPLE HOP FOR DISTANCE SCORES IN ATHLETES RETURNING TO SPORT

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1. INTRODUCTION

Surgical treatment and rehabilitation programs for anterior cruciate ligament reconstruction (ACLR) remain a costly burden to health care services (23). Approximately two thirds of patients successfully return to sport (48); however, re-injury rates are high (~ 35%), occurring to either the reconstructed graft or the contralateral ACL (49). To minimise the risk of re-injury, return-to-sport (RTS) test batteries are used as part of the rehabilitation process to ensure neuromuscular function recovers as close to their pre-injury levels as possible.

Research has previously identified between-limb functional differences in lower limb strength (14), peak power (30), and range of motion (8). However, asymmetrical control of joint torques upon drop jump landings, which leads to between-limb differences in dynamic knee valgus, has also been recognised as a potential risk factor for ACL injury (12). Furthermore, the commonly used threshold of 15% has previously been noted as a lower limb isokinetic muscle strength cut-off above which injury risk is magnified (6). Between-limb asymmetries are a common outcome of ACLR, with studies reporting post-surgical deficits in knee joint moments in the operated limb during both stop-jump landings at 6 and 12 months post-surgery (3) and over ground running ≥12 months post-surgery (38). Read et al. (40) demonstrated that soccer players presented with significant concentric impulse asymmetry >9 months post ACLR, while Butler et al. (3) reported that between-limb asymmetries in knee extension moments can persist up to 12 months post-surgery. Cumulatively, the research indicates functional deficits can remain present in ACLR athletes and that modification of lower limb function following ACLR can be a long-term process.

Practitioners will use a combination of clinical and functional tests to assess RTS readiness (15). Hop tests are reliable field-based functional assessment tools that are easy to use and time efficient (32, 37, 41). Common tests involve the single hop for distance, 6-m timed hop, triple hop and crossover hop for distance (35, 41). Asymmetries in hop distance, or time, are typically determined using the limb symmetry index (LSI), which expresses function of the injured limb as a percentage of the non-injured limb. While some concerns exist with regards to the abnormal mechanics in the non-injured limb influencing the LSI (16), clinical practice often adopts the recommendation that athletes should achieve an LSI of >90% in hop tests as part of their RTS criteria (17). However, emerging evidence indicates that compensatory strategies can be developed in order to achieve symmetrical hop distances and caution should be applied when using arbitrary LSI thresholds (e.g. > 90% LSI) for all variables (7, 16).

Research has shown that hop distance during single leg hopping protocols is positively related to clinical performance variables, such as isokinetic knee extension torque (24, 33) and vertical jump height (20), whilst also being strongly associated with patient self-reported outcome measures (42). However, research has also indicated that hop testing was unable to predict RTS outcomes at 12 months (9, 47) and are not always associated with ACL re-injury rates (18, 28, 29). Thus, in-line with recent literature, further insights to examine the utility of current hop testing protocols and their ability to identify residual between-limb deficits is warranted (7, 29).

Of the available evidence, the triple hop for distance (relative to stature and LSI) has revealed the strongest predictive ability for re-injury (31). While some of the criterion validity of the triple hop test is conflicting (22), it is a commonly used hop test by practitioners that requires the patient to perform three consecutive maximal effort hops in a straight line. The LSI is typically calculated using total distance; however, this performance variable fails to provide insight into the distance the athlete covers with each hop and importantly fails to characterise the manner in which the athlete interacts with the ground during consecutive hops. Rebound tasks such as the triple hop utilize the stretch-shortening cycle, which includes rapid eccentric loading at the point of ground contact, followed by a brief period of amortization, and finally a concentric muscle action (27). Longer amortization indicates reduced ability to absorb and regenerate ground reaction forces upon landing (4, 45) and this may be an evident compensatory strategy following ACL reconstruction (26). This athletic ability has been quantified using reactive strength indices in drop jumping tasks (11), but to the author's knowledge no studies have employed this focused approach in more commonly used tests such as the triple hop for distance which may limit their clinical utility or association with secondary ACL injury (29).

In light of the existing literature, the current study aimed to examine the discriminative ability of the LSI threshold >90% using total hop distance versus reactive strength ratios of individual hops during a triple hop test, in a cohort of ACLR patients during their discharge assessment ≥6 months post-surgery. The hypothesis for the study was that a LSI > 90% in reactive strength ratios from individual hops would provide better discriminative ability compared to a LSI >90% for total hop distance.

2. METHODS

2.1 Participants

Twenty male professional soccer players (24.6 ± 4.2 years; height 175.3 ± 10.2 cm; mass 73.6 ± 14.5 kg) volunteered to take part in the study. All participants underwent surgical reconstruction using an autograft, with 76% and 24% selecting a bone patellar bone graft and hamstring tendon graft (semitendinosus and gracilis) respectively. A priori power analysis was conducted using G*Power3 v. 3.1.9.6 (10) to test the difference between two dependent group means using a one-tailed test, a moderate effect size (d = 0.60), and an alpha of 0.05; results indicated that a total sample of n = 19 was required to achieve a power of 0.80. The mean time from surgery at the time of testing was 36 ± 10.5 weeks (range 24 – 58 weeks). Inclusion criteria required athletes to be male, having undergone unilateral ACL reconstruction, and competing as a registered elite soccer player within one of the recognized competitive leagues of the Qatar Football Association prior to their injury. Players were excluded if they reported a previous ACL injury or surgery to either the involved or contralateral limb. Informed written consent and ethical approval were obtained prior to commencement of testing. The study was approved by the Aspetar Orthopaedic and Sports Medicine Hospital institutional review board and the Anti-Doping Laboratory (ADLQ), Doha, Qatar (IRB: F2017000227).

2.2 Procedures

Experimental design

All tests were performed as part of the institution's athlete discharge assessment process which is required for athletes to complete their rehabilitation. Prior to testing, a practical demonstration and verbal instructions were provided for all protocols. All players had completed the tests previously and were regularly familiarized with the protocols during their rehabilitation. A standardized warm up was first undertaken consisting of light jogging and dynamic stretching. Athletes then completed two agility tests and the single hop for distance (not included in this study), and following a 5 minute rest period then performed the triple hop tests. Three practice trials of the triple hop were performed on each leg in accordance with previous research to reduce the presence of a learning effect (32) and to ensure technical competence, which was determined by the principal investigator. Participants were asked to refrain from strenuous physical activity and eat according to their normal diet in the 24 hours prior to testing. Two recorded trials were performed on both the non-operated and operated limb in that order, with 30 seconds of rest provided between trials.

Triple hop for distance

The triple hop for distance has been shown to display acceptable reliability, with standard errors of measurement of ~3-5% (41). Hop distances were recorded using a tape measure marked out to a length of 10 m. Contact time (s) data were collected via a floor-level optical measurement system (Optojump, Microgate, Italy) with two tracks of bars (one transmitter and one receiver) positioned 1 m apart and connected for the entire 10 m capture distance. This system has been shown to be reliable and valid in comparison to criterion force plate data (44). Players began by standing on the designated test leg with their toe on the marked starting line, and the hip of the free leg flexed at 90° to minimize contralateral propulsion. Participants were instructed to hop forward as far as possible using an arm swing, landing on the same leg and aiming to minimize ground contact time before immediately propelling themselves forward into each consecutive hop. Players were required to stick the final landing and hold their position for two seconds without any other body part touching the floor. A schematic of the triple hop protocol is provided in *figure 1*. The distance travelled from the start line to the heel was recorded to the nearest 0.1 cm, with the average of two trials used for subsequent analysis.

Figure 1 near here

Variables

Contact times (s) and flight times (s) were calculated instantaneously for each individual hop within the capture area using the manufacturer's software. Reactive strength ratios (RSR) were subsequently calculated as the ratio between contact time and flight time (21). The limb symmetry index (LSI) was reported as a percentage and calculated for each variable according to the formula: [operated limb/non-operated limb]*100.

2.3 Statistical analysis

Descriptive statistics (mean ± SD) were calculated for each player across all variables. A paired samples t-test was used to compare performance on operated versus non-operated limbs for total hop distance. Differences in CT, FT and RSR were analysed using a 2 x 2 (limb x hop) repeated measures ANOVA, where "limb" denotes operated vs non-operated limbs and "hop" refers to hop 1 vs hop 2. The level of significance was set at an alpha level $p < 0.05$. Cohen's effect sizes (d) were also calculated to interpret the magnitude of asymmetry using standardized mean differences of <0.2, 0.2-0.49, 0.5-0.79, and 0.8 for trivial, small, moderate, and large effect sizes, respectively. The number of players achieving the pass criteria (>90% LSI) was also calculated for each metric and across both hops as this is the most common method of reporting 'pass/fail' in RTS tests. All data were computed through Microsoft Excel® 2010, with paired samples t-tests and ANOVA processed using SPSS® (V.22. Chicago, Illinois).

3. RESULTS

Descriptive statistics for each variable, inclusive of LSI, and absolute values for the operated and non-operated limbs are displayed in *table 1*.

Between-limb comparisons

Significant between-limb differences and small to moderate effect sizes were shown for triple hop distance. Significant main effects in flight time and RSR were reported for hop and limb, but there were no significant hop x limb interactions. This was confirmed with both flight time and RSR being significantly lower in the operated limb during both hops, with moderate to large effect sizes. There was a significant main effect in contact time for hop, however there was not a significant hop x limb interaction. Differences in contact times between the operated and non-operated limbs were small and non-significant. The greatest limb symmetry deficit was present for RSR; however, LSI values of >90% were reported for all variables.

Table 1 near here

Within-limb comparisons

Mean performance differences were evident between the two recorded hops for all variables on both the operated and non-operated limb. Notably, flight times in both the operated (d = 1.13) and non-operated limbs (d = 1.67) were significantly longer for hop 1 compared to hop 2 ($p < 0.05$), while RSR in both the operated (d = 1.01) and non-operated (d = 0.97) limbs were significantly lower during hop 1 compared to hop 2 ($p < 0.05$). Contact time in the non-operated limb was significantly shorter in hop 2, but the difference between hops in the operated limb failed to reach significance ($p > 0.05$); however, the differences in contact time in either limb were trivial and small respectively (d = -0.18; d = -0.22). All other differences between steps for each variable (including the LSI%) for both the operated or non-operated limb were non-significant and trivial.

Group and individual LSI pass rates

Despite trivial, non-significant mean differences in LSI% for flight time, contact time and RSR between hop 1 and hop 2, variability in the frequency of those achieving the pass criteria were evident for each variable. Group means and individual variability in the LSI% for RSR for both hops are presented in *Figure 2*. During hop 1, 35% of participants passed the >90% LSI threshold, while 45% passed the threshold during hop 2. These data were in contrast to the number of participants (80%) that achieved the LSI threshold for total hop distance. Pass rates for flight time (65% hop 1, 75% hop 2) and contact time (70% hop 1, 60% hop 2) also showed discrepancies in the number of individuals passing the LSI% threshold. Of note, only 60% of participants achieved the same outcome (pass/fail) on each hop, while only 30% and 40% percentage of participants achieved a pass score on all variables for the first and second hops, respectively.

Figure 2 near here

4. DISCUSSION

The current study aimed to examine the reactive strength capabilities of individual hops during a triple hop for distance in a cohort of ACLR patients ≥ 6 months post-surgery. Results showed small, significant differences between limbs for total hop distance. Data also indicated that RSR was significantly lower in the operated limb during both hops (moderate effect), and that large, significant differences in RSR were evident between the first and second hop on both operated and non-operated limbs. While mean LSI% for all variables across both steps exceeded the >90% LSI threshold for total hop distance, individual variation within hops was clearly evident. Despite 80% of participants passing the LSI threshold for total hop distance, only 35% and 45% of participants passed the threshold for RSR during the first and second hops respectively. Cumulatively, these data indicate that using a >90% LSI threshold for reactive strength ratios from individual hops provides better discriminative ability to identify residual deficits in reactive strength capabilities of the operated limb in individuals following ACLR, compared to a >90% LSI threshold for total hop distance. Consequently, the original hypothesis in the current study was accepted.

Successfully returning to play following ACLR requires patients to satisfy criteria within both clinical and functional RTS assessments, with the triple hop for distance protocol often used as part of a functional test battery (17). Total hop distances on the operated (5.03 ± 0.41 m) and non-operated limbs (5.22 ± 0.43 m) reported in this study were very similar to those previously stated in the literature for male athletes (16). Similarly, participants displayed limb asymmetries for triple hop distance at ~6 months post-ACLR, which is commensurate with previous research that showed strength and hop test asymmetries persisted in male ACLR patients 6-9 months post-surgery (16, 39, 51). While the non-operated limb may also exhibit declines in muscle strength as a result of ACL injury (5), the heightened muscle weakness and reduced reactive strength function in the operated limb is a plausible explanation for the magnified asymmetries during hopping protocols (37). This notion is relevant when interpreting the sub-analysis of the composite variables of RSR in the current study. Moderate and large, significant between-limb differences in flight times and small, non-significant differences in contact times were evident during both hops. These findings indicate that while contact times remained similar between both limbs, the operated limb was unable to absorb and regenerate comparative propulsive force during ground contact, thereby resulting in the reduced flight times, shorter individual hops and a reduced total hop distance. Research has shown significant reductions in muscle cross-sectional area (46), fiber force production (19) and impaired corticospinal excitability (34) in ACLR athletes; and while speculative, the reduced flight times in the current study could likely be a combination of undesirable morphological and neuromuscular adaptations that result in reduced strength and power abilities.

Studies which have examined triple hop for distance performance in ACLR patients have typically failed to report discrete differences between hops, instead analysing asymmetries based on the entirety of the test performance (i.e. total distance). While total triple hop distance provides an objective performance measure for clinicians and is often reported in the literature (13, 36, 43), failure to distinguish between the movement characteristics of individual hops during the test may mask potential deficits that remain undetected and ultimately the clinical utility to identify risk of future injury (29). In the current study, large significant differences between hops for RSR were evident, with both operated and non-operated limbs producing a lower RSR during the first hop compared to the second hop. This result implies that participants were less able to react explosively upon ground contact during the first hop in comparison to the second hop, which could be symptomatic of reduced reflexive stiffness regulation. Given that RSR is calculated as the ratio between flight time and contact time, the longer flight times recorded in the second hop, in the absence of any meaningful change in contact times, would explain the increased RSR. Within the triple hop, momentum will likely increase stretch loads and force production during consecutive hops, which could mechanistically drive the heightened RSR in the second hop compared to the first.

Within the current study, data for RSR indicated significant main effects for both hop and limb, but the limb x hop interaction was not significant. Thus, the RSR was consistently lower in the operated limb across both hops, but the between limbs deficits did not necessarily increase from the first to second hop. However, the demands of performing multiple hops in series is likely a better means to examine the deficits in the functional status of both knees as opposed to a single hop. Research has shown that post ACLR, athletes can display reduced eccentric deceleration impulse, slower vertical jump contraction times and greater asymmetry in countermovement jump concentric phase kinetic impulse (25). Such characteristics would be indicative of reduced knee extensor strength and power deficits that would undermine stretch-shortening cycle function. Given the lack of interaction in the current study, it would appear that post ACLR the reactive strength capabilities of the operated limb consistently underperformed compared to the non-operated limb. Therefore, in addition to examining individual hops, practitioners are encouraged to examine alternative variables such as RSR when analysing triple hop performance to better understand functional performance in ACLR athletes.

The sole use of > 90% LSI thresholds for functional hop tests has previously been questioned owing to the risk of masking movement deficiencies during functional tasks (16). The current study revealed no significant mean differences in LSI% for flight time, contact time or RSR, between hops 1 and 2; however, pronounced individual variability was shown for each variable across the study cohort with respect to the frequency of individuals achieving the pass criteria for all variables. For example, while mean LSI% for RSR in the operated limb was similar in both hops at a group level, only 35% and 45% of participants satisfied the > 90% LSI threshold for RSR in the first and second hop, respectively. This finding was in contrast to 80% of participants achieving the LSI threshold for total hop distance and provides further credence to examining individual hops during functional hop testing. These findings also illustrate that hop distance alone is insufficient to determine readiness to RTS and may over-estimate knee function, due to the low number of athletes that 'passed' the test using this criterion (i.e. > 90% LSI) for RSR. Previous research has reported LSI values of 78% for RSI in male team sport athletes 9 months post-ACLR (26); however, their study included a drop vertical jump, whereas we measured RSR during a horizontal task. This further highlights the task and variable dependent nature of asymmetry (2). Thus, the current study underlines the need to consider variability in individual performance during each hop and test variable when interpreting functional status of the lower limb post-ACLR. This approach is needed to better identify those patients who remain at a potentially heightened risk of re-injury due to residual deficits in physical characteristics required for effective performance and knee joint stabilization.

When interpreting the findings from this study, some limitations should be noted. Firstly, the use of the optical measurement system to quantify hop performance only provided contact time, flight time and RSR data and did not provide insight into the kinetics or kinematics associated with each ground contact as an indicator of movement performance. However, previous research has typically only reported total hop distance for this protocol; therefore, this study provides original insight not only with respect to the variables reported, but also the examination of individual hops and how athletes may alter their hop strategy following ACLR. Secondly, the study used a single post-operative time point in which athletes were performing a discharge assessment prior to RTS; thus, the exact time course to note temporal recovery in reactive strength capabilities in ACLR patients remains somewhat unclear, which may warrant further research. Similarly, it is necessary to evaluate whether the use of RSR during individualized hop analysis can discriminate those athletes that remain uninjured versus those that experience future re-injury; if future utility is found, these analytics could support better rehabilitation practice and injury risk targets for practitioners. Finally, much like the LSI the RSR is a ratio, which can potentially mask information about movement strategies and can be altered by changes in either of the composite variables (21). However, contact times and flight times were reported in the current study which aids in the interpretation of the RSR results. Notwithstanding these limitations, the current study provides novel and impactful data that can be used to help inform RTS screening assessments for ACLR patients and may help direct future empirical studies.

5. CONCLUSIONS

This study has shown that alternative functional hop test metrics such as RSR can be used to identify existing limb deficits in patients who are in the final stages of rehabilitation post ACLR that were not apparent when using the more traditional analysis of total hop distance. When using the triple hop as part of a RTS criteria, clinicians are encouraged to examine a wider range of variables, and importantly the individual hops within each trial to identify individual variation in performance that might be masked when solely assessing total hop distance. Literature has highlighted the merits of assessing movement kinematics during single leg hop testing using simple 2D video analysis to identify potential movement deficits (50). Further, recent technological advancements have provided clinicians with affordable, reliable and valid mobile phone application that can be used to assess the mechanics of human locomotion (1). Using the high-speed recording capabilities of the iPhone (240 frames per second), the *Runmatic* application identifies the contact and flight times of each step, which could then be used to determine RSR.

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FIGURE CAPTIONS

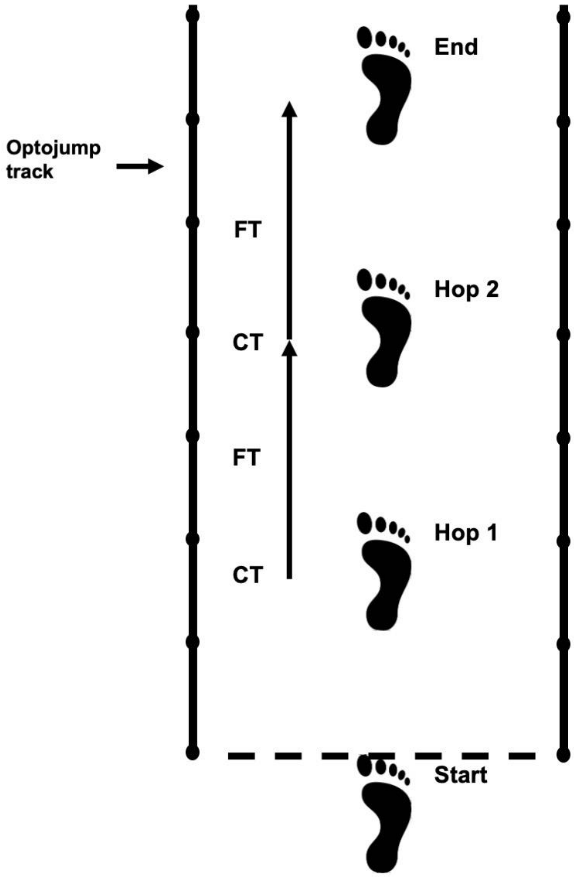

Figure 1. Schematic of the triple hop protocol

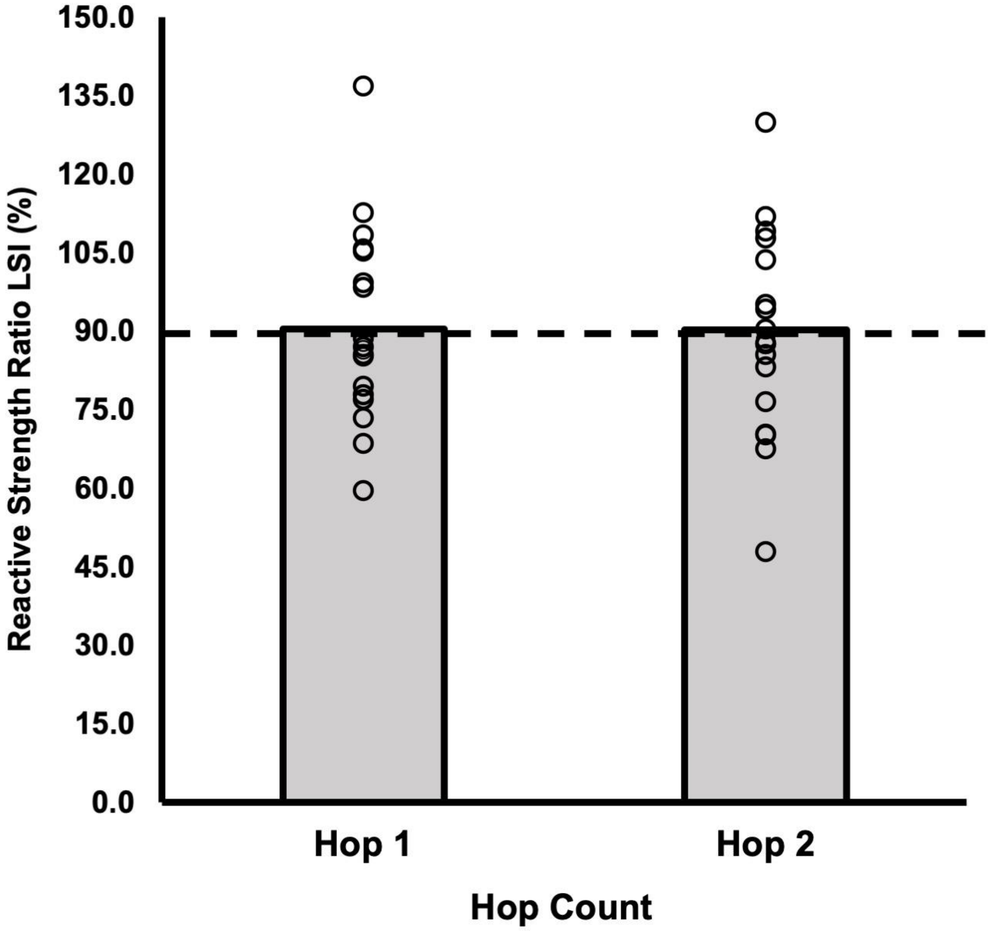

Figure 2. Limb symmetry index (LSI%) for reactive strength ratio (RSR) during both hops of the triple hop protocol. Dashed line indicates the 90% LSI threshold, grey bars represent group mean LSI%, while clear circles represent RSR LSI% for each individual.

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Table 1. Mean (± *sd*) for each limb

	Operated	**Non-operated**	**Between-limb effect size (*d*)**	**LSI%**
Triple hop distance (m)	5.03 ± 0.41	5.22 ± 0.43*	0.45	96.5 ± 5.9
Contact time (s) Hop 1	0.35 ± 0.04	0.34 ± 0.06^	-0.20	96.5 ± 13.6
Contact time (s) Hop 2	0.34 ± 0.05	0.33 ± 0.05	-0.20	96.6 ± 13.3
Flight time (s) Hop 1	0.28 ± 0.03^	0.30 ± 0.03*^	0.67	93.7 ± 10.5
Flight time (s) Hop 2	0.32 ± 0.04	0.35 ± 0.03*	0.85	93.5 ± 11.0
RSR Hop 1	0.81 ± 0.12^	0.92 ± 0.17*^	0.75	90.4 ± 17.5
RSR Hop 2	0.97 ± 0.19	1.09 ± 0.18*	0.65	90.3 ± 18.9

RSR = reactive strength ratio
* significantly different to operated limb in same step ($p < 0.05$)
^ significantly different to Hop 2 in same limb ($p < 0.05$)