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# INTER-DAY RELIABILITY LEG, KNEE AND ANKLE STIFFNESS MEASURES DURING HOPPING

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The purpose of this study was to investigate the inter-day reliability of a common method used to measure and calculate leg, ankle and knee joint musculoskeletal stiffness ($K_{Leg}$, $K_{Ank}$, $K_{knee}$) during hopping. Limited research exists on the reliability of lower extremity musculoskeletal stiffness measures; therefore the reliability of many common methods employed in research studies on hopping has not been adequately established. Twenty active male participants performed one trial of 15 single and double-legged hops at 2.2Hz and at a self-selected frequency during two sessions, separated by 3-7 days. Excellent reliability was shown for $K_{Leg}$ regardless of whether the pace was controlled or self selected, however $K_{Ank}$ and $K_{Knee}$ exhibited only moderate reliability results.

**KEY WORDS:** leg stiffness, joint stiffness, reliability, hopping.

**INTRODUCTION:** Lower extremity musculoskeletal stiffness (MSS) is considered to be an important factor in musculoskeletal performance and injury (Butler et al., 2003; Williams et al., 2004; Williams et al., 2001). During activities such as hopping, an energy exchange exists between the muscles, tendons, ligaments, and bones to provide effective and efficient movement (Cavagna & Kaneko, 1977). The behaviour of this type of energy exchange is described by the spring-mass model whereby a mass (human body) is supported by a spring (leg or lower limb), and the ratio of ground reaction force to the compression of the leg-spring is used to describe the equivalent spring demands of the activity. This ratio is called leg stiffness ($K_{Leg}$) and depicts linear motions of the body that occur in the vertical direction. Furthermore, the contribution of individual joints can also be modelled and are compared to rotational springs that provide stiffness under torsional loads (Arampatzis et al., 2001).
The influence of $K_{Leg}$ and joint stiffness on sports performance has been highlighted throughout the literature. During hopping, $K_{Leg}$ has been shown to be influenced by hopping frequency (Hobara et al., 2010a), surface stiffness (Farley et al., 1998) and ground contact time (Hobara et al., 2007). Similarly, ankle and knee stiffness ($K_{Ank}$ and $K_{Knee}$) are also affected by jumping height (Farley & Morgenroth, 1999), hopping frequency (Hobara et al., 2010a) and surface stiffness. More specifically, $K_{Ank}$ is the major determinant of $K_{Leg}$ during hopping at 2.2 Hz (Farley et al., 1998; Farley & Morgenroth, 1999) and $K_{Knee}$ is the major determinant of $K_{Leg}$ during maximal hopping at a self-selected frequency (Hobara et al., 2009). In sporting populations, $K_{Leg}$, $K_{Ank}$ and $K_{Knee}$ have been shown to be greater in power-trained compared to endurance athletes (Hobara et al., 2007), and is also greater in endurance than untrained athletes (Hobara et al., 2010b).
Musculoskeletal stiffness has been commonly investigated during hopping tasks. As a result, $K_{Leg}$ reliability has been established (McLachlan et al., 2006). Whilst the reliability of specific biomechanical methods to measure $K_{Ank}$ (McLachlan et al., 2006) and $K_{Knee}$ (Allison et al., 1998) has been established, there appears to be a paucity of research investigating the reliability of methods assessing MSS during hopping using kinematic and kinetic data collected via 3-dimensional motion analysis systems. Therefore, the current study attempted to establish the reliability of a laboratory-based, biomechanical assessment of leg, knee and ankle joint stiffness.

**METHOD:** Twenty active males from various sporting backgrounds were recruited from the Australian Catholic University School of Exercise Science to participate in this study (age:

22.3 ± 3.0 years, mass: 74.7 ± 5.6 kg, stature: 1.79 ± 0.7 m). The study was approved by University Ethics Committee and all participants provided written informed consent prior to participating in this study. All participants were injury-free at the time of testing and had not missed a training session or game in their respective sports six weeks preceding the time of testing.

The participants were required to attend two days of testing at the same time of day. The time between testing sessions was 3 – 7 days to avoid any effects from the previous session. A standardized warm-up was performed consisting of 5 minutes of cycling on an ergometer (Monark AB, Sweden) and 5 minutes of stretching prior to testing. The participants were required to hop at 2.2 Hz and their own, self-selected frequency with their hands on their hips and knees locked to reduce knee flexion and to increase the input from the ankle joint (Hobara et al., 2007). Hopping frequency was controlled by a metronome for the 2.2 Hz condition (Cherub, model WMT-555, China), and those trials were accepted if hopping frequency was within ± 2% (Farley et al., 1998). As many practice trials as necessary were given for the participant to become familiar with the protocol. One trial of 15 single (left and right) and double-legged hops was performed with the order of each task randomised to reduce the possibility of an order effect.

A six-camera VICON motion analysis system (Oxford Metrics Limited, U.K.) was used to collect kinematic data at 100 Hz. Retroreflective markers were placed unilaterally on each segment of the lower body according to the requirements of the plug-in-gait model of VICON. The participants were instructed to hop on a force platform (Kistler, model 9268BA, Switzerland; 1000 Hz), and contact with the force plate was set using a 15N trigger.

The kinetic and kinematic data were processed using custom written software (LabVIEW, National Instruments, Version 8.2, U.S.A.). The spring-mass model was used to represent the overall stiffness of the leg (Butler et al., 2003). Leg stiffness was calculated by

$$K_{Leg} = \frac{F_{Peak}}{\Delta L}$$

where $F_{Peak}$ is the peak vertical ground reaction force during landing, and $\Delta L$ is the displacement of the centre of mass during the braking phase of ground contact. The displacement of the centre of mass was calculated by integrating the vertical acceleration twice with respect to time (McMahon & Cheng, 1990). Acceleration is obtained by dividing force by total mass. The braking phase was defined as from initial ground contact to maximum joint flexion. Joint (ankle, knee) stiffness was calculated as the ratio of joint moment ($\Delta M$) to joint angular displacement ($\Delta\theta$) as shown in the equation below (Gunther & Blickhan, 2002). Joint moment was computed through VICON using the inverse dynamics approach (Winter, 1990).

$$K_{Joint} = \frac{\Delta M}{\Delta \theta}$$

All participants displayed right-sided limb dominance. All statistical data were analysed using SPSS (Version 17.0, Chicago, IL). The data were checked for normality using the critical appraisal approach recommended by Peat and Barton (2005). Reliability statistics used were: intra-class correlations (ICC), effect size (ES), and, coefficient of variation ($CV_{ME}$%). Measurement error (ME) was calculated as per Peat and Barton (2005). Statistical significance was set as $\alpha = 0.05$.

**RESULTS:** This study investigated the reliability of a method commonly used to measure musculoskeletal stiffness during hopping at 2.2 Hz and self-selected (SS) frequency. Descriptive and reliability statistics for $K_{Leg}$, $K_{Ank}$ and $K_{Knee}$ over the two testing sessions are shown in Table 1. Hopping frequency during the SS frequency tasks was 1.90 Hz for both legs and 2.12 Hz for both left and right legs.

There were no differences between sessions ($p$ > 0.05) for hopping frequency or for any of the MSS measures. Reliability results (ICC, $CV_{ME}$% and ES) for $K_{Leg}$ during all tasks indicate that there is sufficient reliability except for SS $K_{Leg}$ on the right leg. Intraclass correlation results for $K_{Ank}$ ranged from $r$ = 0.61 to 0.91 and $K_{Knee}$ from $r$ = 0.68 – 0.88. Effect sizes for

MSS variables were all small or trivial except for the moderate vales for 2.2 $K_{Ank}$ and 2.2 $K_{Knee}$ using both legs. However, coefficient of variation results showed that the majority of variables had a greater than 10% variation, with 2.2 $K_{Leg}$ and SS $K_{Leg}$ during the both-legged task and 2.2 $K_{Leg}$ during the left and right-legged tasks being the only tests that had ≤ 10% variation which is considered small (Bennell et al., 1999). For comparison with other studies in the literature, 95% LoA are also provided in Table 1.

**Table 1**
**Musculoskeletal stiffness reliability during hopping at 2.2 Hz (2.2) and self-selected (SS) frequency using left, right and both legs together**

| | | Day 1 | Day 2 | | | | |
|---|---|---|---|---|---|---|---|
| | Test | Mean (SD) | Mean (SD) | ICC | $CV_{ME}$% | ES | 95% LoA |
| Both | 2.2 $K_{Leg}$ | 57.72 (6.46) | 57.87 (5.15) | 0.82 | 5.48 | 0.03 | 15.19 |
| | 2.2 $K_{Ank}$ | 0.31 (0.12) | 0.27 (0.14) | 0.61 | 27.92 | -0.62 | 77.34 |
| | 2.2 $K_{Knee}$ | 0.44 (0.20) | 0.44 (0.21) | 0.88 | 22.09 | 0.82 | 60.20 |
| | SS $K_{Leg}$ | 50.05 (10.65) | 47.84 (10.18) | 0.86 | 10.00 | -0.21 | 28.24 |
| | SS $K_{Ank}$ | 0.25 (0.09) | 0.30 (0.08) | 0.86 | 35.28 | 0.53 | 97.72 |
| | SS $K_{Knee}$ | 0.32 (0.14) | 0.32 (0.20) | 0.85 | 24.64 | 0.01 | 68.25 |
| Left | 2.2 $K_{Leg}$ | 49.62 (9.73) | 51.03 (8.17) | 0.84 | 9.17 | 0.09 | 20.90 |
| | 2.2 $K_{Ank}$ | 0.14 (0.09) | 0.13 (0.07) | 0.71 | 38.03 | 0.41 | 105.34 |
| | 2.2 $K_{Knee}$ | 0.27 (0.13) | 0.24 (0.14) | 0.79 | 51.02 | 0.22 | 141.34 |
| | SS $K_{Leg}$ | 37.62 (9.42) | 39.27 (6.73) | 0.61 | 16.14 | 0.20 | 54.62 |
| | SS $K_{Ank}$ | 0.16 (0.10) | 0.18 (0.10) | 0.91 | 22.46 | 0.12 | 63.70 |
| | SS $K_{Knee}$ | 0.32 (0.20) | 0.34 (0.13) | 0.83 | 26.25 | 0.75 | 72.71 |
| Right | 2.2 $K_{Leg}$ | 46.82 (7.17) | 48.90 (6.23) | 0.89 | 7.55 | 0.04 | 20.90 |
| | 2.2 $K_{Ank}$ | 0.22 (0.09) | 0.18 (0.07) | 0.68 | 28.09 | -0.29 | 77.80 |
| | 2.2 $K_{Knee}$ | 0.17 (0.09) | 0.20 (0.09) | 0.68 | 29.08 | -0.17 | 80.55 |
| | SS $K_{Leg}$ | 39.51 (7.67) | 41.71 (9.14) | 0.20 | 19.72 | 0.26 | 54.62 |
| | SS $K_{Ank}$ | 0.16 (0.08) | 0.16 (0.06) | 0.86 | 23.00 | 0.09 | 63.70 |
| | SS $K_{Knee}$ | 0.26 (0.13) | 0.25 (0.13) | 0.82 | 26.02 | 0.10 | 72.06 |

Units for $K_{Leg}$ are kN/m and for $K_{Knee}$ and $K_{Ank}$ Nm/kg/deg. ICC, intraclass correlation; $CV_{ME}$%, coefficient of variation as a percentage of measurement error; 95% LoA, 95% limits of agreement.

**DISCUSSION:** This study attempted to investigate and establish the reliability of a testing protocol used to measure MSS during hopping at 2.2 Hz and at a self-selected frequency. Our results demonstrated good reliability for $K_{Leg}$ during all tasks at 2.2 Hz however, mixed reliability for $K_{Ank}$ and $K_{Knee}$. When investigating $CV_{ME}$% statistics, all $K_{Ank}$ and $K_{Knee}$ results exhibited greater than the desired 10% for reliability and moderate to good ICCs, deeming them to have a modest reliability overall. All means, ICCs and ES for $K_{Leg}$ compare well with past research (Hobara et al., 2010a; Lloyd et al., 2009; McLachlan et al., 2006). Means for $K_{Ank}$ and $K_{Knee}$ are also congruent with other research (Hobara et al., 2010a) however, it is difficult to compare our reliability results to other studies due to methodological differences and the lack of published measurement error data (McLachlan et al., 2006). A potential explanation for why reliability results during the SS task were moderate may because this task was not indicative of movements similar to the spring-mass model. Furthermore, as the $CV_{ME}$% suggests, there is evidence of measurement or movement variability within this protocol when measuring $K_{Ank}$ and $K_{Knee}$ and this may be an important finding in itself.

**CONCLUSION:** The current study concluded that the method detailed in this paper is reliable for measuring $K_{Leg}$ for single (left and right) and double-legged hopping in active males. This suggests that the current methodology to measure $K_{Leg}$ is suitable for assessing injury prediction or performance during a controlled task (2.2 Hz) or a task more ecologically valid to sport (self-selected frequency). The lack of measurement reliability for $K_{Ank}$ and $K_{Knee}$ may suggest that inherent movement variability exists in hopping to provide a flexible movement strategy that may protect the joint from overload. This inherent movement variability may or may not be overcome with a familiarization session and requires further investigation.

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