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A study of the reproducibility and reliability of the musculo-articular stiffness of the ankle joint

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ABSTRACT

The objective of this work was to evaluate the reproducibility, reliability and usefulness of the musculo-articular stiffness (MAS) of the ankle joint, measuring it by the free vibration technique. Seventeen (nine males and eight females) healthy university students were included in the study. Force (f), MAS (k) and unitary MAS (k_u) (defined as the ratio between the value of stiffness k obtained in the test *(absolute terms)* and the value of force (f)) were obtained. A test-retest protocol was designed and performed on the same day to determine the short-term reproducibility of f, k and k_u. Short-term reproducibility of k and k_u on 1 day in absolute terms ($<$ 7% Coefficient of Variation (CV)) and relative reproducibility (Intraclass Correlation Coefficient (ICC) and Pearson $\geq$ 0.97) for both feet were obtained. The reliability of k and k_u in absol$_u$te terms ($<$ 9% CV) and in relative terms (ICC and Pearson $\geq$0.93) based on repeating the protocol for 1 week was analysed for both feet. To analyse the usefulness, the Effect Size (ES) ratio = "Trivial" for all variables (for 1 day and 1 week) and the Smallest Worthwhile Change (SWC) ratio (Typical Error (TE) < SWC) = "GOOD" for k and k_u (1 day and 1 week) were considered. The Minimal Difference needed to be considered "real" (MD) for $k_u \cong$ 3.5% (1 day); $k_u \cong$ 8.5% (1 week) ($p < 0.05$) was obtained. The statistical analysis carried out displayed the high reproducibility, reliability and usefulness of the MAS test, which was more consistent with k_u than k. Therefore, the unitary stiffness (k_u) proven to be representative of the mechanical response of the ankle joint obtained by free vibration techniques, which allows comparison between different subjects.

1. Introduction

The use of stiffness to evaluate the mechanical behaviour of muscle-tendon units (MTUs) has been widely accepted in the scientific literature in past decades, as reported in the comprehensive review by Ditroilo et al. (2011b).

Generally speaking, the concept of stiffness associated with a deformable body (consequently applicable to the MTU) implies that, for a given applied load, a corresponding elongation appears. A stiffer (less compliant) body will require more load to achieve a certain level of elongation.

A stiffer MTU has multiples advantages: for instance, it may be able to transmit contractile force to the skeletal segment more efficiently and rapidly (Walshe et al., 1996; Watsford et al., 2010). From a mechanical point of view, a stiffer MTU exhibits more opposition to deformation, more energy being then stored associated to the same level of elongation. Consequently, a stiffer musculo-tendinous structures may induce greater elastic energy return during the shortening phase of the stretch–shortening cycle (Lacour and Bourdin, 2015). In any case, the interpretation of the mechanical response of the MTU for the analysis of aspects as locomotion is a much more complicated question. Thus, for instance, the compliance of the MTU has also been identified to have some advantages during locomotion (Biewener, 1998; Mörl et al., 2016).

Therefore, the stiffness parameter is a significant factor related to muscle function (Wilson et al., 1991; Wilson et al., 1994), to general athletic performance (Heise and Martin, 1998; Walshe and Wilson, 1997), and in particular to the performance during fast and slow SSC movements (Chelly and Denis, 2001; Ditroilo et al., 2011a, b; Walshe and Wilson, 1997; Wilson et al., 1994).

Various methods have been reported in the scientific literature to obtain the stiffness linked to the MTU in different parts of the body. The aim of the present work focused on the stiffness obtained by the application of free vibration techniques. Numerous methods to assess stiffness using single and multi-joint protocols based on various mathematical models have been used for the ankle joint (Ditroilo et al., 2011b; Faria et al., 2009; Fukashiro et al., 2001; Hunter and Spriggs, 2000; Kongsgaard et al., 2011; McLachlan et al., 2006; Murphy et al.,

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2003; París-García et al., 2013; Shorten, 1987). Alternatively, innovative in-vivo approaches to identify non-linear MTU parameters can be found in Penasso and Thaller (2017) and Siebert et al. (2007). Other factors that may influence the MTU stiffness measurement, as is the case of antagonistic muscles, skin, and articular capsule, have been considered in a pioneering study (Christensen et al., 2017).

The applications of the above methods (free vibration techniques) to obtain the stiffness of the MTU gave rise to the consistent use of the term musculo-articular stiffness (MAS) (Ditroilo et al., 2011b) (henceforth k). MAS is a global measure of stiffness that incorporates not only the muscle-tendon structure but also skin, ligaments and articular surfaces (Rabita et al., 2008). Various assessments have demonstrated that MAS is a relevant parameter, as higher MAS values are associated with superior muscular performance (e.g., Murphy et al., 2003; Watsford et al., 2010; Wilson et al., 1994) and higher levels of functional capacity (Faria et al., 2009, 2010).

The k value can be obtained from a wide variety of methodologies, making the comparison of data among studies very difficult. Studies that have focused on obtaining the k of the ankle joint have utilized several experimental approaches. Some of them obtained the mechanical response of the ankle joint (traditionally linked to the triceps surae) using the free vibration technique (Babic and Lenarcic, 2004; Blackburn et al., 2006; Faria et al., 2009; Fukashiro et al., 2001; McLachlan et al., 2006; Murphy et al., 2003; París-García et al., 2013; París-García, 2010). Among them, only Babic and Lenarcic (2004) used a procedure based exclusively on the rotation of the foot around the ankle articulation. The remaining procedures were based on the vertical displacement of the lower leg (Blackburn et al., 2006; Faria et al., 2009; Fukashiro et al., 2001; McLachlan et al., 2006; Murphy et al., 2003; París-García et al., 2013).

To establish the representativeness of k (related to the ankle joint), different proposals have been developed related to the construct validity of free-oscillation techniques. Some proposals have related k to the rate of torque development (RTD), the ratio of maximum force developed (RFD) and electromechanical delay (EMD), (Ditroilo et al., 2011a; Watsford et al., 2010; Wilson et al., 1992). Among available research, strong reliability of a test of lower body stiffness was previously reported (Walshe et al., 1996). Furthermore, other proposals reported very good reliability for unilateral ankle stiffness (Murphy et al., 2003) and acceptable reliability for bilateral ankle stiffness (McLachlan et al., 2006).

All procedures considered above yield a k value from a force registered at a measuring device in one test. This implies that a subject with larger anthropometric characteristics or greater weight when placed on the measurement device will apply higher force at the load cell and will obtain higher values of k regardless of the level of fitness.

The unitary stiffness k_u, which is derived from the ratio between the value of stiffness k obtained in the test *(absolute terms)* and the value of force (f) registered at the measurement device for one subject (obtained in the same test), is used in the present work. This parameter allows us to compare one subject in two different moments or two subjects with different heights or weights. The strict control of the position of the subject during the test avoids large variations in the measured force, nevertheless the influence in the determination of k will be taken into account by the proposed normalization procedure (k_u).

Because k obtained by these procedures in absolute terms is largely affected by the influence of other variables such as anthropometric measures, it is also necessary to analyse the behaviour of these other variables in test-retest protocols of this parameter (k_u). This would allow us to make comparisons at different times and between different subjects. For this purpose, statistical analyses were carried out in accordance with other previous studies (Buchheit et al., 2010; Ferrete et al., 2014).

In summary, the aim of the present work was to evaluate the reproducibility, short-term reliability and usefulness of the entire process that would permit accurate unilateral assessment of k and k_u related to the ankle joint response based on the free vibration technique.

2. Methods

2.1. Subjects

Seventeen healthy active university students (9 males and 8 females) [age (mean 23.13) (SD 2.85) years, mass (mean 68.69) (SD 14.20) kg, height (mean 174.81) (SD 9.57) cm] volunteered to participate in the current study. All subjects were medically screened (visual inspection and a questionary about previous injuries or surgeries in the lower limb) to determine their health and exercise habits prior to testing and to ensure they did not have any previous injury to the lower body musculature. Prior to testing, all subjects attended a familiarization session (detailed explanation of the whole procedure) which involved performing all test items, with particular attention to the lower body stiffness test. Each subject gave written informed consent to participate in the study, which was approved by the University Ethics Committee of University of Seville.

2.2. Research design

To evaluate the reproducibility and reliability of the procedure, the subjects had to visit the laboratory twice with one week between visits (see Fig. 1). The same protocol (which will be explained in detail in Section 2.3) was followed the two days of testing to standardize any other effects. The sample size used in the reliability study was consistent with the sample sizes used in previous reliability studies related to obtaining musculo-articular stiffness (MAS) around the ankle articulation (Ditroilo et al., 2011b).

Subjects were instructed to refrain from vigorous lower body exercise 48 h prior to each test day and required to maintain a constant routine. Although all subjects were tested in the whole range of admissible loads (París-García et al., 2015), only the information corresponding to half of the body weight (Zinder et al., 2007) was considered in this paper to evaluate the reproducibility of the measurements. A percentage of the maximal voluntary contraction (MVC) might also been used by researchers to stablish the load employed (Walshe et al., 1996).

To obtain k and k_u, 2 consecutive tests on the same leg were carried out. Subjects were familiarized with the protocol during the first visit to the laboratory. The data from the first and second days of the protocol and their differences were used in the present study of the reliability of the procedure. An identical procedure was carried out with the contralateral leg. The individual test duration was less than 5 s and sufficient recovery time (3 min) between tests was given.

2.3. Test protocol

2.3.1. Warm-up

Participants warmed up by cycling at 100 W for 5 min maintaining cadence between 60 and 70 rpm. During this time, an explanation of the entire testing protocol was given.

2.3.2. Musculo-articular stiffness

The test considered in this work to obtain k, defined as MAS of the muscles linked to ankle articulation, was based on the free vibration technique (París-García et al., 2013).

The response of the subject corresponded to that of a damped single degree of freedom (DOF) system and is associated with the vertical displacement of the shank linked to rotation of the ankle articulation.

The subject adopts a position in the test, see Fig. 2a, so that the lower body is capable of attenuating the vibration originated by a disturbance, thus assumed to act as a damped single DOF system. The disturbance is generated by the free fall of a mass, the height and weight being always the same, thus the impact energy is constant for all

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