PARAMETRIC STUDY OF MUSCULO-ARTICULAR STIFFNESS OBTAINED BY FREE VIBRATION TECHNIQUE

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The aim of this study was to analyse the effect of several variables on musculo-articular stiffness (MAS) linked to ankle articulation using free vibration techniques. Twenty one university students participated in the present study. The outcomes: 2nd metatarsal head moment arm (*R*), Achilles tendon moment arm (*r*), the ratio of both (*R/r*), force (*f*), MAS (*k*) and a unitary MAS (k_u). Independent samples t-tests and One-way ANOVA with repeated measures were carried out. Results: Across gender, very significant differences in *k* values ($p<0.001$), *R* values ($p=0.000$) and *r* values ($p<0.001$). Conversely, no significant differences in k_u values ($p=0.14$) or *R/r* values ($p>0.622$). Conclusions: Anatomical symmetry obtained implies mechanical symmetry and the differences of *k* obtained across gender may be due to differences in size.

KEY WORDS: free vibration technique, musculo-articular stiffness, moment arm, laterality, gender.

INTRODUCTION: A simple way to define the stiffness is the relationship between an applied load and the amount of elastic deformation that occurs in a structure. Since one stiffer muscle–tendon unit (MTU) exhibit more resistance to deformation, it can store more energy (Ditroilo, Watsford, Murphy, & De Vito, 2011). The stiffness of the MTU is related to performance during fast and slow stretch shortening cycle (SSC) movements (Wilson, Murphy, & Pryor, 1994).
Different proposals suggest that leg stiffness is dependent on the stiffness of torsional joint spring (related to ankle articulation). This joint stiffness, is defined as the ratio of the maximal joint moment to the maximum joint flexion at the middle of the stance phase (dynamic analysis. This concept of stiffness related to articulation is defined as Musculo-articular stiffness (MAS) by Ditroilo et al. (Ditroilo et al., 2011). In this sense, the free vibration technique has been shown to be a reliable and valid way to obtain the MAS (McLachlan, Murphy, Watsford, & Rees, 2006)
Some authors, focusing on getting more and more specific sport training, carried out biomechanical studies where bilateral analysis between the dominant and non-dominant side are conducted. This biomechanical difference between both sides, linked to the ankle joints during physical activities, may be related to the physiological and anatomical symmetries or asymmetries of the lower extremities (Niu, Wang, He, Fan, & Zhao, 2011). Several authors did not find significant difference between bilateral limbs in limb length, rearfoot angle, or navicular drop (Shultz & Nguyen, 2007). Conversely, other authors obtained significant differences for anthropometric measures of bilateral limbs that are very important to the MAS values (rearfoot angle, size and shape of footprint or anterior knee laxity and others) (Livingston & Mandigo, 2003)
Therefore, the aim of the present work is to carry out a parametric study, using the free vibration technique in order to analyze the effect of different variables such as laterality, gender or anthropometric characteristics on the MAS values around ankle articulation.

METHODS: Twenty one healthy, active, university students (12 males and 9 females) [(mean ± SD) age 23.38 ± 3.01 years, mass 67.48 ± 13.78 kg, height 173.86 ± 9.97 cm]

volunteered to participate in the current study. All subjects were medically screened to determine their health and exercise habits prior to testing and to ensure no previous injury to the lower body musculature. Each individual gave written informed consent to participate in the study, which was approved by the Ethics Committee of The University of Pablo de Olavide.
Firstly, the anthropometric measures of the set (height and weight) and all the anthropometric measures of the feet needed to obtain variables referring to stiffness: moment arm of 2nd metatarsal head (*R*), Achilles tendon moment arm (*r*) and the ratio of both measures (*R/r*) for both feet, were taken.
The details of how these measurements were obtained using ad hoc and noninvasive procedures based on footprints are described in a previous proposal by the same authors (In press). Finally, several physiological measurements were obtained, such as the unilateral musculo-articular stiffness (MAS), using the free vibration technique for both sides (left leg (*Ll*) and right Leg (*RL*). To obtain these measurements, the subjects adopt a specific position at a measurement device designed previously by the same authors (París-García, Barroso, Cañas, Ribas, & París, 2013).
All data were analyzed using SPSS statistical software (version 20). Independent samples *t*-tests were performed to identify group differences between both sides and gender differences related to the anthropometrical variables of the foot (moment arm length of 2nd metatarsal head (*R*), moment arm length of the Achilles tendon (*r*) and the ratio of both (*R/r*). One-way ANOVA with repeated measures was used to detect the significant effects of laterality and gender on stiffness (*k*), Unitary Stiffness (*k/f*) and force registered. *F*-values in the ANOVA, Tukey's post hoc test of critical difference, were used to locate significance between means.

RESULTS: The values of *R*, *r* and *R/r* are presented in tables 1 taking into account the following different aspects: i) Differences between both sides (left foot and right foot); ii) Differences across gender.
In table 1, it can be observed that there is no significant difference (p>0.05) between both sides for *R, r* y *R/r*. These differences between the mean values for both sides are lower than 3.5% for all variables.
The mean values of the same variables are displayed taking into account the gender differences. On the one hand, very significant differences can be observed across genders for *R* and *r* (p<0.001) and on the other, these differences between males and females cease to be significant when *R/r* is variable in the analysis (p=0.62).
The values of *f*, *k* y k_u (mechanical response) are displayed in table 2: i) Taking into account whether the subject is right-handed or left-handed; ii) taking into account gender differences.

Table 1
Anthropometric data for the foot. Side and gender analysis.

anthropometric variables	Side	Mean Value (SD)	Difference (%)	Paired t-test p-value^b	Difference of mean value (95% Cis of the difference in mean	Gender	Mean Value (SD)	Difference (%)	Paired t-test p-value^b	Difference of mean value (95% Cis of the difference in mean
R moment arm (cm)	Right foot Left foot	14,3 (1,4) 14,4 (1,2)	0,1 (0,7%)	0,8580	-0,18 (-0,80-0,67)	Male Female	15,19 (0,7) 13,34 (0,78)	2,56 (17,51%)	0,000*	1,84 (1,37-2,30)
r moment arm (cm)	Right foot Left foot	4,4 (0,5) 4,5 (0,4)	0,1 (2,2%)	0,4290	0,80 (-1,69-0,39)	Male Female	4,68 (0,37) 4,2 (0,4)	0,48 (10,9%)	0,000*	0,47 (0,23-0,71)
R/r	Right foot Left foot	3,3 (0,5) 3,2 (0,3)	0,1 (3,03%)	0,2860	-1,081 (0,32-0,99)	Male Female	3,25 (0,31) 3,2 (0,39)	0,3 (1,55%)	0,622	0,53 (-0,165-0,27)

^{b}p<0,05 for significant difference *p<0,001 for very significant difference

The results in table 2, show that the differences between both sides in relation to mechanical response are not significant (p>0.05).

Table 2
Values for *f*, *k*, k_u taking into account the laterality and gender analysis.

					ANOVA ONE FACTOR					ANOVA ONE FACTOR
mechanical parameters	**Laterality**	N	Mean Value (SD)	Typical errors	F (p-value)	**Gender**	N	Mean Value (SD)	Typical errors	F (p-value)
	Left hand	10	1252,93 (207,19)	65,52		Male	12	1318,61 (264,50)	53,99	
***f* (N)**	Right hand	32	1112,80 (315,8)	55,83	1,72 (0,20)	Female	9	916,24 (144,11)	33,96	33,94 (0,00[b])
	Total	42	1146,17 (297,45)	45,90		Total	21	1146,16 (297,45)	45,89	
	Left hand	10	277,54 (59,98)	18,97		Male	12	310,75 (95,1)	19,41	
***k* (KN/m)**	Right hand	32	277,79 (97,90	17,31	0,00 (0,99)	Female	9	233,68 (59,95)	14,04	15,36 (0,000*)
	Total	42	277,72 (89,65)	13,83		Total	21	277,72 (89,64)	13,83	
	Left hand	10	0,23 (0,03)	0,01		Male	12	0,236 (0,3074)	4,82	
k_u **(k/f)** $(m^{-1} \cdot 10^{-3})$	Right hand	32	0,25 (0,05)	0,01	1,61 (0,21)	Female	9	0,256 (0,5609)	3,12	2,22 (0,14)
	Total	42	0,24 (0,04)	0,01		Total	21	0,244 (0,4401)	3,87	

[b]p<0,05 for significant difference *p<0,001 for very significant difference

Males have very significantly higher values for *f* and *k* than females (p<0.001) (table 2). However, females have slightly higher values for k_u than males this difference not being significant (p=0.14).

DISCUSSION: The aim of this research was to carry out a parametric study of MAS (*k*) and unitary MAS (k_u) values, in order to analyze the influence of laterality, gender or anthropometrical characteristic on both feet. Firstly, given the disparity of results for anthropometric differences between both lower limbs when considering the literature, the results obtained for the set of samples show a clear symmetry, as in some previous proposals (Shultz & Nguyen, 2007). These results are important because they have a great influence on the mechanical response obtained. In this sense, the results of the mechanical response were in the same way obtaining very similar values for both lower limbs.
Regarding the analysis of the influence of gender on anthropometric characteristics, large differences in *R* and *r* were found but not in *R/r (R/r being* the measurement of a proportionality parameter). These differences found in *R* and *r* may be due to anthropometric differences between subjects of both genders (Paris-Garcia, Barroso, Doblare, Canas, & Paris, 2015).
Finally, large differences were found between males and females in *f* and *k* values. A higher value for *f* implies greater weight which has an associated higher *k* value. Therefore, the value of K_u takes into account the value of f allowing comparisons between subjects. Although females obtained lower values than males for *k*, they obtained slightly higher values for k_u, but these differences were not significant.

CONCLUSION: There is no clear correlation between laterality and anthropometric characteristics for both feet. The observed anatomical symmetry corresponds to symmetry in the mechanical response for both lower limbs. With regard to the influence of gender, significant differences (p>0.05) were not found when a proportionality parameter such as *R/r* is compared. The influence of gender on stiffness is high in absolute terms for the sample studied but is negligible in relative terms. Therefore, K_u and *R/r* are better for assessing the MAS parameter when comparing different subjects.

REFERENCES:

Ditroilo, M., Watsford, M., Murphy, A., & De Vito, G. (2011). Assessing musculo-articular stiffness using free oscillations: theory, measurement and analysis. Sports Medicine, 41(12), 1019–32.

Livingston, L. A., & Mandigo, J. L. (2003). Bilateral rearfoot asymmetry and anterior knee pain syndrome. The Journal of Orthopaedic and Sports Physical Therapy, 33(1), 48–55.

McLachlan, K. a, Murphy, A. J., Watsford, M. L., & Rees, S. (2006). The interday reliability of leg and ankle musculotendinous stiffness measures. Journal of Applied Biomechanics, 22(4), 296–304.

Niu, W., Wang, Y., He, Y., Fan, Y., & Zhao, Q. (2011). Kinematics, kinetics, and electromyogram of ankle during drop landing: a comparison between dominant and non-dominant limb. Human Movement Science, 30(3), 614–23.

Paris-Garcia, F., Barroso, a., Doblare, M., Canas, J., & Paris, F. (2015). Evaluation of the stiffnesses of the Achilles tendon and soleus from the apparent stiffness of the triceps surae. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 229(1), 28–39.

París-García, F., Barroso, A., Cañas, J., Ribas, J., & París, F. (2013). A critical study on the experimental determination of stiffness and viscosity of the human triceps surae by free vibration methods. Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine, 227(9), 935–54.

Shultz, S. J., & Nguyen, A.-D. (2007). Bilateral asymmetries in clinical measures of lower-extremity anatomic characteristics. Clinical Journal of Sport Medicine : Official Journal of the Canadian Academy of Sport Medicine, 17(5), 357–61.

Wilson, G. J., Murphy, A. J., & Pryor, J. F. (1994). Musculotendinous stiffness: its relationship to eccentric, isometric, and concentric performance. Journal of Applied Physiology, 76(6), 2714–2719.

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