Analysis of the relation between flexibility and passive stiffness of the hamstrings

Cecília Ferreira de Aquino[1], Gabriela Gomes Pavan Gonçalves[2], Sérgio Teixeira da Fonseca[3] and Marisa Cotta Mancini[4]

ABSTRACT

Introduction: The terms s*tiffness* and *flexibility,* which refer to muscle properties, are frequently used as synonymous in the literature. However, these two muscle properties have distinct definitions. **Objective:** To investigate the contribution of the measure of flexibility to the passive stiffness of the hamstrings. **Methods:** Stiffness and flexibility were measured in 33 healthy individuals. An isokinetic dynamometer registered the resistance torque offered by the hamstrings during knee passive extension at 5º/s. Muscle activity was monitored during the tests to guarantee electromyographic silence. The slope of the torque-angle curve was used to determine the hamstrings passive stiffness. The range of the test was divided into three portions to calculate the stiffness of the 1st, 2nd and 3rd thirds of knee movement. Flexibility was assessed by having the examiner move the lever of the dynamometer in the direction of knee extension. The final measure was determined as the angle at which movement was interrupted because the examiner perceived a resistance to further movement and the volunteer reported a sensation of discomfort. Simple regressions were used for statistical analysis. **Results:** The regression analysis demonstrated correlation values of r = –0.48 (R^2 = 0.23; p = 0.005), r = –0.54 (R^2 = 0.29; p = 0.001), r = –0.46 (R^2 = 0.21; p = 0.007) and r = –0.45 (R^2 = 0.20; p = 0.008) between flexibility and total, 1st, 2nd and 3rd third stiffness, respectively. **Conclusion:** Despite significant associations between the analyzed variables, flexibility explains only a low percentage of the variability of the stiffness measure. Stiffness and flexibility are not equivalent and should be analyzed independently.

Keywords: Muscle. Energy. Injury.

INTRODUCTION

The passive stiffness and flexibility muscular properties are frequently investigated in rehabilitation and sports studies fields(1-2), being considered synonyms and indistinctly used by many authors of these fields(3). However, these properties present differences in relation to their definitions found in the literature. Passive muscular stiffness is defined as the reason between the change in the muscle tension by change unit in its length, when it is elongated without contraction activity(4). On the other hand, flexibility is defined as the ability of the muscular tissue to elongate, allowing that the articulation moves through the whole movement's breadth(5). These conceptual definitions of stiffness and flexibility guide the investigations about the contribution of these muscular properties to the functional and sports performance.

Muscular stiffness is a mechanical property of the muscle related to the resistance of this tissue to deformation, being graphically represented by the slope of the stress-strain curve(6). The area below this curve represents the amount of energy absorbed by the muscle when it is elongated, either in rest or contracted(7). Thus, the stiffness contributes to the muscle's ability to absorb energy under mechanical forces(8-9). The amount of energy applied on the musculoskeletal structures during the sports and functional activities seems to determine the occurrence of lesion of these structures(7,10). Therefore, the bigger the stiffness of the muscular tissue, the bigger its ability to absorb energy and the lower its susceptibility to lesion. Moreover, the absorbed energy by the muscular tissue can be stored and, then, reused in the subsequent movement in order to trigger the muscular action(1,11). Thus, the stiffness and the energy absorption ability of the muscle can help not only in the prevention of muscular lesions, but also in the performance improvement during the movement.

Flexibility property is frequently used as a means of inference over the muscular length(12). Although the maximum excursion of the muscle is not usually necessary in routine activities(13), significant losses of this property may compromise the suitable execution of the movement(2,14). Despite some authors' suggestion that the flexibility reduction would be associated to a higher musculoskeletal lesions frequency(15-17), it is not proved that the flexibility gain has influence on these lesions prevention(18-19). The lack of demonstration of this effect may be explained by the use of different evaluation methods of the flexibility(17), varied criteria to determine muscular shortening(19), besides the lack of standardization in the definition of the term lesion(17). Therefore, the real impact of the flexibility as means of the muscular length, in the occurrence of lesions and in the functional performance, needs to be better investigated.

Clinical and research data suggest that the stiffness is inversely related to the muscular flexibility, that is, more rigid muscles would invariably be less flexible and, on the contrary, less passively rigid muscles would have more flexibility(15,17,20). These data are based on the mathematical formula that defines stiffness, expressed as the force variation (ΔF) divided by the length variation (ΔL). Once this length variation can be considered as a flexibility measurement, the presence of this common denominator would imply in an inversely proportional relation between these two properties. Some authors also consider the passive stiffness as being a flexibility component, using similar operational ways to measure both properties(16,21). The flexibility usually functions as the movement's breadth of an articulation for a determined force capable of promoting the muscle's elongation which goes through it(22). On the

1. Mestre em Ciências da Reabilitação, UFMG, Professora do Curso de Fisioterapia da Fundação Educacional de Divinópolis.
2. Fisioterapeuta, Aluna do curso de Especialização em Fisioterapia, ênfase em Ortopedia e Esportes, do Departamento de Fisioterapia da Escola de Educação Física, Fisioterapia e Terapia Ocupacional da Universidade Federal de Minas Gerais.
3. Doutor em Ciências, Boston University, Professor Adjunto do Departamento de Fisioterapia da Escola de Educação Física, Fisioterapia e Terapia Ocupacional da Universidade Federal de Minas Gerais.
4. Doutora em Ciências, Boston University, Professora Adjunta do Departamento de Terapia Ocupacional da Escola de Educação Física, Fisioterapia e Terapia Ocupacional da Universidade Federal de Minas Gerais.

Received in 17/8/05. Final version received in 25/11/05. Approved in 12/5/06.

Correspondence to: Cecília Ferreira de Aquino, Rua Grão Mogol, 320/601, Sion – 30310-010 – Belo Horizonte, MG. E-mail: cferaquino@yahoo.com.br

other hand, due to the direct measurement impossibility, the muscle's passive stiffness in humans is quantified through the relation between the resistance torque offered by the articulation and the breadth of movement during the passive articulator dislocation[23]. Thus, the operational definitions of stiffness and flexibility demonstrate that the investigation of these properties contribution for the functional and sports performance should consider the existing conceptual differences between these properties and use measurement procedures corresponding to such differences.

Further studies which precisely determine the existing relation between flexibility and muscular stiffness, using operational means compatible with the definition of each property are still needed. Thus, the aim of the present study was to investigate the contribution of the measurement of the hamstrings flexibility for the passive stiffness of this muscular group.

METHODS

Sample

The sample of this study consisted of 33 healthy university students, of both sexes (6 males and 27 females), with age range between 18 and 26 years (average of 21,7 ± 1,8). The volunteers could not present lumbar pain history or lesion of the lower limbs. This research was approved by the Ethics Committee in Research from the Universidade Federal de Minas Gerais, having all participants signed a free and clarified consent form, agreeing to participate in the study.

Procedures

After the study's procedures explanation and consent form's signature, the determination of the volunteer's dominant lower limb was done, since the measurements were done only in the non-dominant limb, as a means of standardizing the measures among the volunteers. The limb considered dominant was that chosen by the participant to kick a ball[17]. After that, the participants were submitted to the measurement of the body mass and the leg and foot segments length of this side. The anatomic references used for the measurement of the lengths of the segments were according to the descriptions of the anthropometrical table by Dempster[24].

Evaluation of the passive stiffness

Pairs of surface active electrodes (Biopac System Inc., Goleta, CA), with diameter of 11,4 mm and inter-electrodes distance of 20 mm, were placed over the area of the biggest muscular part of the lateral vast (LV) and femoral biceps (FB) of the non-dominant limb, following the fibers orientation. Before the electrodes placement, the trichotomy and cleansing of the skin with alcohol was done. A land electrode was placed on the acromio.

During the passive stiffness test, the electromyographic activity of the LV and FB was simultaneously collected, which allowed the monitoring of the muscular activity and guaranteed that the test was passively conducted. A MP 150WSW electromyographic was used (Biopac System Inc., Goleta, CA) connected to a computer, with collection frequency of 1000 Hz, entrance avoidance of 2 mega ohms (MΩ) and Rejection of the Common Mode potency of 1000 MΩ. Only the measures in which the activity of both muscles did not exceed the average activity registered during resting increased of two standard deviations above the average were accepted for analysis[25]. A computer program was developed in order to compare the muscular activity presented during the test with resting electromyographic signal, in intervals of 50 ms. The program was applied right after each measurement, in the interval between the repetitions, hence allowing or rejecting the test.

The passive stiffness was evaluated through a isokinetic dynamometer (Biodex Medical System Inc., Shirley, NY). Such device has a passive mode of operation, which moves the desired articulation at a constant velocity, in predetermined breadths, registering the resistance torque offered against the movement. The individual was sat at the isokinetic dynamometer, with the pelvis stabilized and the chest perpendicular to the seat. The thigh of the non-dominant limb was placed on a lever set on the knee proximal region, raising it at an horizontal position so that the hip was at 110 degrees of flexion during the test. This positioning was used in order to guarantee that none of the participants would reach the complete breadth of the knee extension, avoiding that the tension of the articular structures, such as the posterior capsule, would influence in the measure[23]. The knee articular axis was aligned with the rotation axis of the dynamometer and the lever arm positioned above the lateral malleoli.

After the positioning of the volunteer, the dynamometer lever was placed in the horizontal position and a level measuring device was used in order to determine the 0 degree position. The maximum knee flexion position, according to the device permission, was determined as the initial test position. The final position was defined with the knee articulation being displaced by the examiner in the extension direction and the displacement being interrupted when the participant reported discomfort related to the posterior muscles of the thigh. The passive mode of the dynamometer at a 5°/s velocity was used in order to perform the passive articulation movement in the extension direction[23]. Five consecutive preliminary measures were taken so that the individual could experience the movement and in order to decrease the viscoelastic effects of the muscle's stretching before the stiffness measure[9,23,26]. Afterwards, three measures of the passive stiffness were performed, with one minute interval between them, with the aim to apply the program of muscular activity verification. The average of the obtained values in these three measures was used. During the passive movements, the isokinetic dynamometer software registered the resistance torque of the articulation, without correction by the effects of the torques produced by the lever mass and the leg and foot segments. At the end of this test, a complete repetition of the lever movement of the dynamometer in the extension orientation was performed, without the participant's lower limb placement, with the aim to register the torque generated by the lever mass for later correction of this torque over the stiffness measure.

Reliability tests (test-retest) presented an intra-class correlation coefficient (ICC) of 0.889 for the test total breadth stiffness (total stiffness) and of 0.849, 0.872 and 0.934 for the stiffness values in the 1st, 2nd, and 3rd thirds of the total movement breadth used in the test, respectively.

Flexibility evaluation

The hamstrings flexibility was evaluated after the passive stiffness test, keeping the same positioning of the participants. During this test, the electromyographic data of the LV and FB were also registered, which allowed the monitoring of these muscles activity. Only the measures in which the activity of both muscles did not exceed the average activity registered in resting increased in two standard-deviations were analyzed[25]. In this evaluation, the examiner passively displaced the knee articulation in the extension direction. The participants were told not to voluntarily resist to the lever displacement, with the movement beginning at maximum flexion allowed by the knee. The final position of the articular movement, used to determine the muscle's flexibility, was defined when the volunteer reported discomfort related to the thigh posterior muscles stretching and the examiner perceived a firm resistance to additional movement of the knee articulation. At that moment, the examiner interrupted the lever displacement, with the flexibility being defined as the articular angle in which this movement was interrupted. Three measures were taken, being the average of these values analyzed.

The reliability test of the flexibility measure presented a ICC of 0.823.

Data reduction

The total stiffness calculation and of the 1st, 2nd and 3rd thirds were performed from the isokinetic dynamometer software data obtained during the passive stiffness test, collected at a 100 Hz frequency. The articular angle was measured in degrees and the resistance torque was measured in Newton-meters (Nm), without gravity's effects correction. The torque values and angles registered by the dynamometer were transferred to a computer for data analysis. The hamstrings stiffness was determined through a program specially developed for this reason. The data were filtered with an ordinary Butterworth filter of 4th order and a cut-off of 0.025 Hz. The program calculated the torques produced by the leg's and foot's weight and by the foot's weight over the leg for the whole breadth, from the data related to the body mass and the segments' length, according to the anthropometrical table by Dempster[24]. The values of these torques and of the torque produced by the weight of the lever in the whole breadth of the movement were subtracted from the passive torque provided by the dynamometer, with the resulting torques being used for the calculation of the passive stiffness of the hamstrings. The measure of the angle was changed to radians (rad) and the passive torque offered by the hamstrings was plotted in relation to the angular dislocation. The stiffness was defined as the torque variation (Nm) divided by the angle variation (rad) and was calculated through an analysis of simple linear regression between the test angles and the passive torque of the hamstrings. The slope of the torque angle curve resulting from the analysis of regression was used in order to determine the passive stiffness of the hamstrings, being expressed in Nm/rad. The test breadth was divided in three equal portions and a calculation of the total stiffness and of the slope of the curves in the 1st, 2nd and 3rd thirds of the angular movement was done (figure 1).

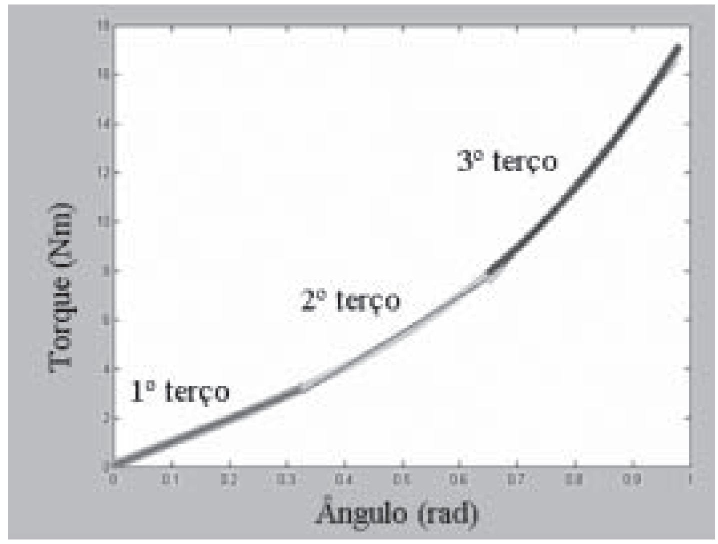

Figure 1 – Illustration of the slope of the torque angle curve of the hamstrings in the test total breadth and in the 1st, 2nd and 3rd thirds of the angular movement

The dynamometer software provided the value of the knee articular angle in which the lever movement was interrupted, used to evaluate the hamstrings flexibility. The angulation in which the movement was interrupted, determined in degrees, and correspondent to the flexibility value, was determined from the figure provided by the software.

Statistical analysis

Simple regression analyses were used to determine the contribution of the flexibility measure for the passive stiffness measures of the hamstrings in the total breadth of the test (total stiffness) and in the 1st, 2nd and 3rd portions of the angular movement (stiffness of the 1st, 2nd and 3rd thirds). The significance level was established in $\alpha = 0,05$.

RESULTS

The simple regression analyses revealed correlation values r = –0.48 (p = 0.005), r = –0.54 (p = 0.001), r = –0.46 (p = 0.007) and r = –0.45 (p = 0.008) between flexibility and total passive stiffness, 1st, 2nd and 3rd thirds, respectively. The determination coefficients were $R^2 = 0.23$, $R^2 = 0.29$, $R^2 = 0.21$ and $R^2 = 0.20$ for the respective comparisons (figure 2).

The averages and standard deviations of the flexibility and stiffness values, in degrees and Nm/rad, respectively, are presented in table 1.

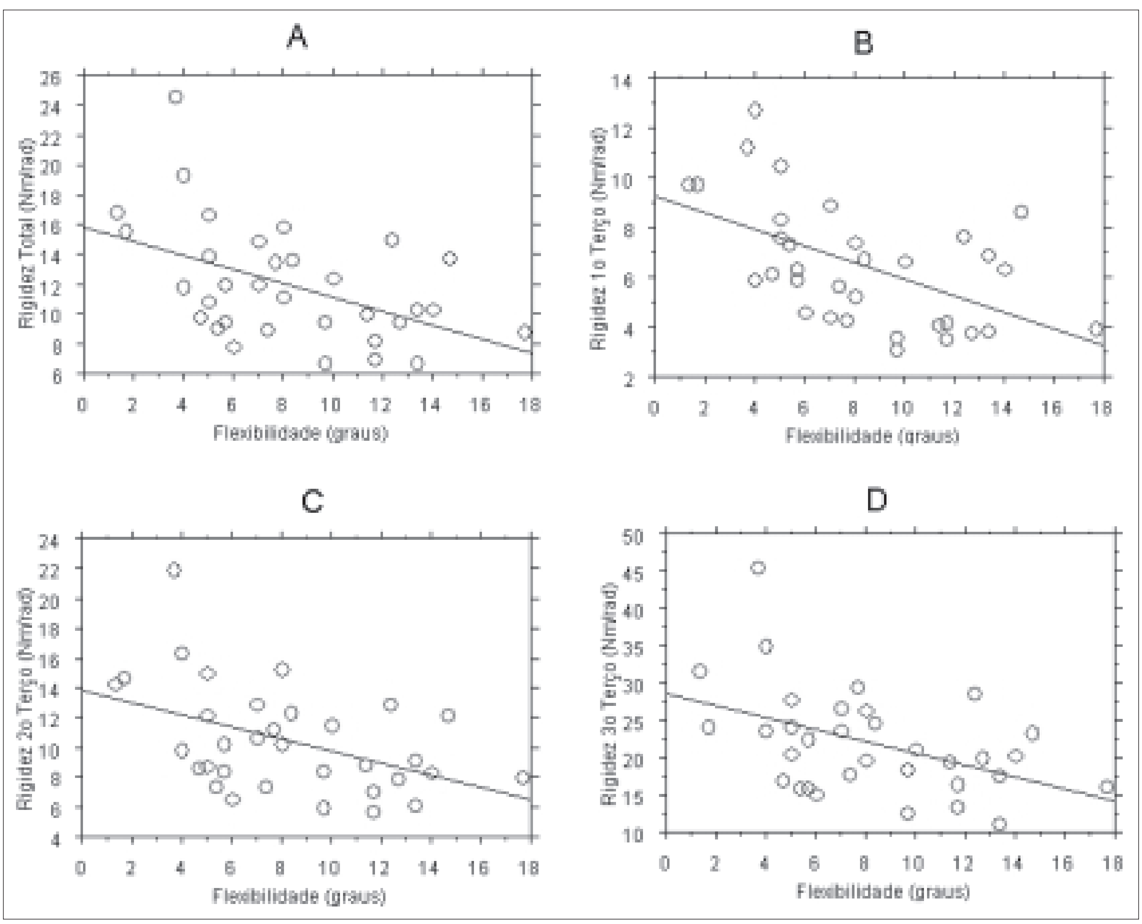

*Figure 2 – Dispersion demonstrating the association between flexibility and: **A)** total passive stiffness; **B)** passive stiffness of the 1st third; **C)** passive stiffness of the 2nd third and **D)** passive stiffness of the 3rd third.*

TABLE 1
Valores médios de flexibilidade (graus) e rigidez passiva (Nm/rad)

Variáveis	Médias	Desvio-padrão
Flexibilidade	8,15	3,98
Rigidez passiva total	11,99	3,92
Rigidez passiva 1º terço	6,38	2,48
Rigidez passiva 2º terço	10,28	3,57
Rigidez passiva 3º terço	21,53	7,04

DISCUSSION

The present study was conducted with the aim to investigate the relation between the flexibility and passive stiffness relation of the hamstrings. According to the obtained results, a percentage relatively small of the total passive stiffness variability measures, of the 1st, 2nd and 3rd thirds (23%, 29%, 21% and 20%, respectively) may be explained by the flexibility measure of this muscular group, despite the associations between these variables being significant.

The R^2 values found in this study suggest the existence of other variables as predicting factors of the passive muscular stiffness. Among these variables, the transversal section area of the muscle[27] and the passive articular structures should be considered[28]. Chelboun *et al.* (1997) demonstrated that the muscular volume is responsible for 84% of the stiffness measure variation of the elbow flexion muscles[27]. Moreover, Blackburn *et al.* (2004) suggest that muscles with bigger tropism would have a greater number of crossed bridges between the actin and miosine filaments, which would contribute for the muscle resistance to deformation[4]. On the other hand, there is evidence that the muscular atrophy observed after a period of immobilization is associated to a decrease of the muscular stiffness[29-30]. Moreover, some authors suggest that a bigger muscular mass indicates a bigger amount of connective tissue, which implies in a bigger number of collagen fibers paralleling positioned, influencing in the resistance to the muscle's deformation as well[14,31]. Thus, the amount of contraction and connective tissue present in the muscle seems to be crucial to the passive stiffness, which possibly limits the contribution of the flexibility to the stiffness measure.

The passive stiffness measure can also be influenced by the resistance offered by articular structures to the articulation dislocation. In the present study, the muscular stiffness was operated as the resistance passive torque found in different articular angles. In this case, on should observe that the knee articulation stiffness was used as synonym for the hamstrings stiffness. Therefore, the measure of the variable passive muscular stiffness also included a possible resistance offered by structures such as skin, connective tissue and articular capsule. Johns and Wrigth (1962) observed in guinea pigs that the muscular tissue is responsible for 41% of the total passive articular stiffness, with the capsule contributing with 47% and the tendon with 10% of the total value[28]. Thus, the individuals' positioning during the evaluation of the stiffness was performed to guarantee that the complete breadth of the knee extension would not be reached, consequently avoiding that the tension of the passive components of the articulation influenced in the measure[23]. However, due to the impossibility of directly measure the muscular stiffness in humans, the participation of the passive articular structures may have been favored, minimizing the contribution of the flexibility in the evaluated measure.

The flexibility measure, different from the passive stiffness, can be influenced by the individual's tolerance to the muscle's stretching[22,32-33]. The individual who presents a higher tolerance to the stretching allows the application of a bigger amount of strength over the articulation, leading to higher movement breadth values in the determination of flexibility[34]. The mechanism and structures responsible for the increased tolerance are not known, however, some authors speculate that the free nociceptive terminations present in the articulation and in the muscle would play a role in this process[35]. Thus, the flexibility gain without modifications of the passive stiffness observed after a muscular stretching program, would be more related to an increase of the individual's tolerance to stretching[23,31-32,34]. Some authors justify that stretching does not influence in the passive stiffness due to the non-existence of alterations in the muscle's structure and by the fact that this characteristic dos not suffer influence of the tolerance to stretching[23,32,34]. These findings reinforce the lack of strong association between flexibility and stiffness; once the flexibility, evaluated through the breadth of the articulation's movement changes, may occur in the absence of modification of the passive stiffness.

A proposal of an inverse relation between flexibility and stiffness is base don the mathematical formula that defines stiffness ($\Delta F/\Delta L$), which shows that less flexible muscles that is, which present a low value in the formula's denominator, are stiffer, and would be more prone to lesions[3,15,17,32]. However, one should consider that the formula for the stiffness definition characterizes a relation between strength and length. Therefore, an increase of the ΔL may be observed, which would characterize an increase in flexibility, accompanied by a simultaneous increase in the ΔF. In this case, even if the muscle presented a variation in its length, the stiffness would not alter, which would justify the findings in the study which evaluate changes in flexibility without modification in stiffness Thus, contrary to what has been reported in the literature[3], the flexibility and passive stiffness properties are not synonyms and should be independently analyzed.

The found values in this study are similar to the ones reported by Wilson *et al*, who investigated the association between flexibility and stiffness of the muscles of the shoulder articulation, obtaining a R^2 value of de 0.30[36]. Blackburn *et al* (2004) reported values of moderate and positive correlation between flexibility and passive stiffness of the hamstrings[3]. Although a discrepancy between the studies in relation to the correlations direction due to differences in the measurement techniques is found, the interpretation of these results is similar. However, differently from the studies mentioned before, the present study has chosen to analyze the total curve of the stiffness and the three parts of the curve divided according to the articular angle, once the stiffness behavior is non-linear during the movement[22-23,27]. In the first third of the curve, the torque values were low and the variation coefficients were high. The second third consisted of a transition zone and the third third represented the linear portion of the curve. Hence, there was the possibility that the correlation values between flexibility and passive stiffness would be different according to the portion of the curve analyzed. However, the determination coefficients were similar, with the analysis considering the whole stiffness curve and each one of its three portions. Consequently, even considering the methodological differences in the studies, the results of the present investigation are according to the other findings in the literature.

A possible limitation of this study is related to the method used in order to measure the flexibility. The obtained measure with the use of such method is influenced by the individual's tolerance to stretching and also by variations in the muscle's resistance[23,32]. Another possible limitation refers to the passive stiffness measure of the hamstrings, which as mentioned before, was used as synonym to the knee articulation stiffness, being able to suffer influence from other passive structures. Moreover, the findings of the present study may have been influenced by the higher number of female individuals present in the sample, which limits the generalization of the results. Despite the mentioned limitations in relation to the measurement of the stiffness and flexibility variables and the sample's composition, a factor which contributes to guarantee these measures validation was the monitoring of the electromyographic activity of the muscles which could have influenced in the measure during the tests. Trials in which the electromyographic activity was higher than the one registered in resting, according to criteria established in the literature, were not analyzed[25]. Therefore, the stiffness and flexibility properties evaluated represent properties intrinsic to the muscle in resting, and not a function of the contraction or reflex muscle activity.

The results of the present study show that other variables, different from the flexibility, may be used in order to predict the muscular stiffness. The low correlation values found between flexibility and passive stiffness possibly justify the absence of evidence in the literature in relation to the effects of the flexibility gain in the prevention of musculoskeletal lesions[18-19]. Thus, changes in the tropism and muscular length, more than changes in flexibility, evaluated through the maximum breadth of the articulation movement, should lead future studies with the aim to modify the muscular stiffness trying to optimize the sports performance and decrease the number of musculoskeletal lesions. Little stiff muscles present greater deformation in response to an applied strength[13], which results in a greater amount of articular dislocation, decreasing the articulation's stability which they cross and increasing the probability of articular and ligament lesion[4]. Furthermore, muscles which present a bigger transversal section area and consequently greater stiffness, can absorb bigger amounts of energy, decreasing the susceptibility of the musculoskeletal structures to lesion[8-9]. Thereby, studies that investigate the impact of intervention programs, such as the muscular strengthening and stretching, in the passive stiffness and their potential benefits in the lesions prevention are needed.

CONCLUSION

Although the associations between the variables have been significant, a relatively small percentage of the variability of the total, 1st, 2nd and 3rd thirds of the passive stiffness measures (23%, 29%, 21% and 20%, respectively) can be explained through the measure of the flexibility of this muscular group. Such result indicates the possibility of influence of other variables, such as transversal section area of the muscle, in the determination of the passive muscular stiffness. Finally, one may come to the conclusion that the flexibility and stiffness properties are not synonyms and should be independently analyzed.

All the authors declared there is not any potential conflict of interests regarding this article.

REFERENCES

1. Wilson GJ, Elliot BC, Wood GA. Stretch shorten cycle performance enhancement through flexibility training. Med Sci Sports Exerc 1992;24(1):116-23.
2. Sahrmann SA. Concepts and principles of movement. In: Sahrmann SA. Diagnosis and treatment of movement impairment syndromes. Mosby, 2002;9-50.
3. Blackburn JT, Padua DA, Riemann BL, Guskiewicz KM. The relationships between active extensibility, and passive and active stiffness of the knee flexors. J Electromyogr Kinesiol 2004;14:683-91.
4. Blackburn JT, Riemann BL, Padua DA, Guskiewicz KM. Sex comparison of extensibility, passive, and active stiffness of the knee flexors. Clin Biomech 2004; 19(1):36-43.
5. Malone TR, Garret WE, Zachazewski JE. Muscle: deformation, injury, repair. In: Zachazewski JE, Magee DJ, Quillen WS. Athletic injuries and rehabilitation. Philadelphia: WB Saunders, 1996;71-91.
6. Latash ML, Zatsiorsky VM. Joint stiffness: Myth or reality? Hum Mov Sci 1993; 12:653-92.
7. Garret WE, Jr. Muscle strain injuries: clinical and basic aspects. Med Sci Sports Exerc 1990;22(4):436-43.
8. Garret WE, Jr, Safran MR, Seaber AV, Glisson RR, Ribbeck BM. Biomechanical comparison of stimulated and nonstimulated skeletal muscle pulled to failure. Am J Sports Med 1987;15(5):448-54.
9. Taylor DC, Dalton JD, JR, Seaber AV, Garret WE. Viscoelastic properties of muscle-tendon units. The biomechanical effects of stretching. Am J Sports Med 1990; 18(3):300-9.
10. Mair SD, Seaber AV, Glisson RR, Garret WE, Jr. The role of fatigue in susceptibility to acute muscle strain injury. Am J Sports Med 1996;24(2):137-43.
11. Lindstedt SL, Reich TE, Keim P, LaStayo PC. Do muscles function as adaptable locomotor springs? J Exp Biol 2002;205:2211-6.
12. Bandy WD, Irion JM. The effect of time on static stretch on the flexibility of the hamstring muscles. Phys Ther 1994;74(9):845-50.
13. Singer BJ, Jegasothy GM, Singer KP, Allison GT. Evaluation of serial casting to correct equinovarus deformity of the ankle after acquired brain injury in adults. Arch Phys Med Rehabil 2003;84(4):483-91.
14. Gajdosik RL. Passive extensibility of skeletal muscle: review of the literature with clinical implications. Clin Biomech 2001;16(2):87-101.
15. Hartig DE, Henderson JM. Increasing hamstring flexibility decreases lower extremity overuse injuries in military basic trainees. Am J Sports Med 1999;27(2): 173-6.
16. Krivickas LS, Feinberg JH. Lower extremity injuries in college athletes: relation between ligamentous laxity and lower extremity muscle tightness. Arch Phys Med Rehabil 1996;77(11):1139-43.
17. Witvrouw E, Danneels L, Asselman P, D'Have T, Cambier D. Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. A prospective study. Am J Sports Med 2003;31(1):41-6.
18. Herbert RD, Gabriel M. Effects of stretching before and after exercising on muscle soreness and risk of injury: systematic review. BMJ 2002;325:1-5.
19. Thacker SB, Gilchrist J, Stroup DF, Kimsey CD, Jr. The impact of stretching on sports injury risk: a systematic review of the literature. Med Sci Sports Exerc 2004;36(3):371-8.
20. Halbertsma JPK, Goeken LNH, Hof L, Groothoff JW, Eisma WH. Extensibility and stiffness of the hamstrings in patients with nonspecific low back pain. Arch Phys Med Rehabil 2001;82:232-8.
21. McHugh MP, Connolly DAJ, Eston RG, Kremenic IJ, Nocholas SJ, Gleim GW. The role of passive muscle stiffness in symptoms of exercise-induced muscle damage. Am J Sports Med 1999;27(5);594-9.
22. Magnusson SP, Simonsen EB, Aagaard P, Sørensen H, Kjæ r M. A mechanism for altered flexibility in human skeletal muscle. J Physiol 1996;497(Pt 1):291-8.
23. Magnusson SP, Simonsen EB, Aagaard P, Sørensen H, Kjæ r M. Biomechanical responses to repeated stretches in human hamstring muscle in vivo. Am J Sports Med 1996;24(5):622-8.
24. Winter DA. Anthropometry. In: Winter DA. Biomechanics and motor control of human movement. New York: Wiley and Sons Inc, 1990;51-74.
25. Lamontagne A, Malouin F, Richards CL. Contribution of passive stiffness to ankle plantarflexor moment during gait after stroke. Arch Phys Med Rehabil 2000; 81(3):351-8.
26. McHugh MP, Magnusson SP, Gleim GW, Nicholas JA. Viscoelastic stress relaxation in human skeletal muscle. Med Sci Sports Exerc 1992;24(12):1375-82.
27. Chleboun GS, Howell JN, Conatser RR, Giesey JJ. The relationship between elbow flexor volume and angular stiffness at the elbow. Clin Biomech 1997;12(6): 383-92.
28. Johns RJ, Wright V. Relative importance of various tissues in joint stiffness. J Appl Physiol 1962;17(5):824-8.
29. Jarvinen MJ, Einola SA, Virtanen EO. Effect of the position of immobilization upon the tensile properties of the rat gastrocnemius muscle. Arch Phys Med Rehabil 1992;73:253-7.
30. Gajdosik RL, Vander Linden DW, McNair PJ, Riggin TJ, Albertson JS, Mattick DJ, et al. Slow passive stretch and release characteristics of the calf muscles of older women with limited dorsiflexion range of motion. Clin Biomech 2004;19:398-406.
31. Halbertsma JPK, Mulder I, Goeken LNH, Hof L, Eisma WH. Repeated passive stretching: acute effect on the passive muscle moment and extensibility of short hamstrings. Arch Phys Med Rehabil 1999;80:407-14.
32. Halbertsma JPK, Goeken LNH. Stretching exercises: effect on passive extensibility and stiffness in short hamstrings of healthy subjects. Arch Phys Med Rehabil 1994;75(9):976-81.
33. Magnusson SP, Simonsen EB, Aagaard P, Dyhre-Poulsen P, McHugh MP, Kjær M. Mechanical and physical responses to stretching with and without preisometric contraction in human skeletal muscle. Arch Phys Med Rehabil 1996;77(4):373-8.
34. Halbertsma JPK, Van Bolhuis AI, Goeken LNH. Sport stretching: effect on passive muscle stiffness of short hamstrings. Arch Phys Med Rehabil 1996;77(7): 688-92.
35. Marchettini P, Simone DA, Caputi G, Ochoa JL. Pain from excitation of identified muscle nociceptors in humans. Brain Res 1996;740(1-2):109-16.
36. Wilson GJ, Wood GA, Elliot BC. The relationship between stiffness of the musculature and static flexibility: an alternative explanation for the occurrence of muscular injury Int J Sports Med 1991;12:403-7.