

Relationship between joint passive stiffness and hip lateral rotator concentric torque

Relação entre rigidez articular passiva e torque concêntrico dos rotadores laterais do quadril

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Abstract

Background: Adequate passive stiffness of the hip joint can prevent the occurrence of excessive transverse plane lower limb movement during functional activities. Strength training of the hip lateral rotator muscles can be used to increase the stiffness of this joint. However, the relationship between hip joint passive stiffness and muscle strength remains undocumented in the literature. **Objective:** To investigate the association between hip passive stiffness measured during medial rotation and hip lateral rotator concentric torque in healthy young adults. **Method:** Twenty-six individuals with mean age of 24.42 ± 2.77 years participated in the present study. To quantify hip stiffness, the passive resistance torque during medial rotation was measured using an isokinetic dynamometer. Stiffness was determined by the mean slope of the passive torque curve obtained in the first 20° of motion. Electromyography was used to ensure inactivity of the hip muscles during this procedure. The isokinetic dynamometer was also used for assessment of hip lateral rotator peak torque and work in a range of motion of 55° of rotation. **Results:** Linear regressions demonstrated correlation coefficients of $r=0.70$ ($R^2=0.50/p<0.001$) and $r=0.77$ ($R^2=0.59/p<0.001$) between hip passive stiffness and the measures of lateral rotator peak torque and work, respectively. **Conclusions:** There is a moderate to good association between hip passive stiffness and lateral rotator concentric torque. This association suggests that lateral rotator strength training can increase hip stiffness.

Keywords: passive stiffness; muscle strength; hip; muscle strength dynamometer; rehabilitation.

Resumo

Contextualização: Rigidez passiva adequada do quadril pode impedir movimentos excessivos dos membros inferiores no plano transversal durante a realização de atividades funcionais. O fortalecimento muscular dos rotadores laterais do quadril poderia ser utilizado na tentativa de aumentar a rigidez dessa articulação. No entanto, a relação entre rigidez passiva e força dos músculos do quadril não está documentada na literatura. **Objetivo:** Investigar a associação entre rigidez passiva do quadril durante o movimento de rotação medial e torque concêntrico dos rotadores laterais dessa articulação em indivíduos saudáveis. **Método:** Foram avaliados 26 indivíduos com média de idade de $24,42 \pm 2,77$ anos. Para quantificação da rigidez passiva do quadril, o torque passivo de resistência durante a rotação medial dessa articulação foi mensurado por um dinamômetro isocinético. A rigidez foi determinada como a inclinação média da curva de torque passivo obtida nos primeiros 20° do movimento. Eletromiografia foi utilizada para verificar o repouso dos músculos do quadril durante esse procedimento. O dinamômetro isocinético também foi utilizado para avaliação do pico de torque e trabalho máximo dos rotadores laterais do quadril em uma amplitude de 55° de rotação. **Resultados:** Regressões lineares demonstraram coeficientes de correlação $r=0,70$ ($R^2=0,50/p<0,001$) e $r=0,77$ ($R^2=0,59/p<0,001$) entre rigidez do quadril e as medidas de pico de torque e trabalho muscular dos rotadores laterais, respectivamente. **Conclusões:** Existe associação de moderada a boa entre rigidez passiva do quadril e torque concêntrico dos rotadores laterais dessa articulação. A associação demonstrada sugere que o fortalecimento dos rotadores laterais pode ser eficaz em aumentar a rigidez do quadril.

Palavras-chave: rigidez passiva; força muscular; quadril; dinamômetro de força muscular; reabilitação.

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Introduction

The strength produced by the muscles from the hip joint is commonly studied due to its influence on the performance of functional activities, such as gait, landing from jumps, and running¹⁻³. However, the passive characteristics of the hip joint also deserve attention in the study of human movement. One of the main characteristics is passive joint stiffness, determined by the rate of change of resistance torque during the angular displacement of this joint in the absence of muscle contraction⁴⁻⁶. The mechanical properties of the peri- and intramuscular connective tissues (e.g. ligaments, tendons, fascias) and of muscle proteins provide resistance to joint displacement, being complementary to muscle activation during functional activities⁵⁻⁷. Studies suggest that adequate levels of passive stiffness could reduce the need for muscle contraction to resist movement⁸, cutting the energy expenditure^{9,10} required to promote functional stability. Therefore, investigating hip passive stiffness may facilitate the understanding of the movements of this joint during functional activities.

Reduced values of hip passive stiffness can result in excessive medial femoral rotation during the performance of activities in closed kinematic chain¹¹, possibly leading to excessive subtalar pronation¹². The interdependence of these movements occurs because hip medial rotation favors leg medial rotation, which (due to the malleolar pinch's geometry) facilitates the pronation of the subtalar joint¹³. Excessive medial rotation of the lower limb and subtalar pronation can modify pelvis posture in the frontal and sagittal planes and, consequently, vertebral spine alignment¹⁴. These connections between the segments of the lower limbs and the trunk may explain the documented association of excessive hip medial rotation with the occurrence of musculoskeletal injuries, such as low back pain¹⁵, knee ligament ruptures¹⁶, and patellofemoral pain syndrome^{17,18}. Thus, the use of techniques with the purpose of promoting changes in hip stiffness could be useful for the prevention and rehabilitation of these injuries, considering their effects on lower limbs and trunk kinematics.

There is evidence that joint stiffness is dependent on the cross-sectional area (CSA) and composition of the tissues that surround the joint^{19,20}. Ryan et al.¹⁹ reported a correlation coefficient of 0.83 between the CSA of plantar flexors and passive stiffness during ankle dorsiflexion. Chleboun et al.²⁰ showed correlation coefficients that

ranged from 0.79 and 0.92 between the CSA and passive stiffness of the elbow. These studies suggest that strengthening can be used to modify joint stiffness, since it promotes an increase in muscle volume combined with an increase in the number of parallel elastic components in the muscle^{21,22}. This assumption could be supported by a direct demonstration of association between passive stiffness and muscle strength of the hip joint. Therefore, the purpose of the present study was to investigate the association between passive stiffness during medial rotation of the hip and isokinetic variables that characterize the performance of the lateral rotators of this joint in healthy young adults.

Method

Sample

Twenty-six subjects (17 women) took part in this study. The sample characterization is shown on Table 1. The inclusion criteria were: age between 18 and 35 years, no history of lower limb pain, injury or surgery in the last six months, and hip range of motion of at least 40° of medial rotation and at least 25° of lateral rotation. Shorter ranges of motion can be associated with significant muscle shortening, which could affect torque and stiffness measurements.

The exclusion criteria were: inability to maintain hip muscles relaxed during the assessment of passive torque and presence of pain or discomfort during the tests. All subjects signed an informed consent form agreeing to participate in this study. The study was approved by the Research Ethics Committee of Universidade Federal de Minas Gerais (UFMG), Belo Horizonte, MG, Brazil (protocol no. ETIC 0176.0.203.000-11).

Table 1. Sample Characterization (n=26).

	Mean (Standard Deviation)	Minimum values	Maximum values
Age (years)	24.42 (2.77)	21	35
Body mass (kg)	66.39 (13.07)	51.1	97.5
Height (m)	1.69 (0.1)	1.55	1.87
BMI (kg/m ²)	22.86 (2.61)	17.01	29.43

BMI=body mass index.

Instruments

A scale with height rod and a tape measure were used to measure body mass, height, and length of foot and leg segments. The ranges of hip rotation were measured with a goniometer. The dynamometer Biodex 3 Pro (Biodex Medical Systems, Inc., Shirley, NY, USA) was used to assess the passive resistance torque generated by the hip joint and the lateral rotator concentric torque. A surface electromyograph ME6000 (Mega Electronics, Kuopio, Finland) was used to monitor the electromyographic (EMG) activity of five hip muscles during the passive test.

Procedures

Initially, body mass and height were assessed. The leg and foot segments were measured according to Dempster's anthropometric table²³. The left lower limb was used for the analysis. Active surface electrodes (Ag/AgCl) were placed on the belly of the gluteus maximus, gluteus medius, biceps femoral, tensor fasciae latae, and adductor longus muscles, according to recommendations by Cram, Kasman, and Holtz²⁴. The referencing electrodes used for each of these muscles were placed on the following bony prominences: posterior-superior iliac spine, iliac crest, femoral lateral epicondyle, anterior-superior iliac spine, and femoral medial epicondyle, respectively. Before the electrodes were placed, the skin was shaved and cleansed with alcohol to reduce impedance. After that, the EMG signals were collected with the subjects at rest in ventral decubitus on a treatment table.

Measurement of the passive resistance torque during hip medial rotation

To allow the quantification of hip passive stiffness, the passive resistance torque of this joint was measured along the range of motion of medial rotation. The subject was placed on the isokinetic dynamometer in ventral decubitus, with the hips in neutral in the sagittal plane of movement, with the left knee at 90° of flexion and the pelvis stabilized. The dynamometer axis was aligned with the tibial tuberosity. The lever arm was fixed below the medial malleolus of the ankle (Figure 1), and it moved the subject's lower limb at a constant speed of 5°/s. This speed was chosen to minimize the influence of tissue viscosity on the resistance torque²⁵.

Prior to the test, the subject performed 15 rotation repetitions at the same speed as the test in order to become familiar with the procedures and accommodate the tissue's viscoelasticity. Next, the subject performed three repetitions of the test. The range of motion was set to start at 5° of hip lateral rotation and finish at 25° of medial rotation. Neutral hip joint (0°) was defined as the position in which the tibia was perpendicular to the horizontal plane, evaluated with an inclinometer.

During hip movement on the isokinetic machine, the subjects were instructed to keep hip muscles relaxed. To check if the participants were able to follow this instruction, EMG data from the hip muscles were collected. EMG signals were recorded at a frequency of 1000 Hz and filtered with a fourth-order Butterworth bandpass filter with a cut-off frequency between 30 Hz and 500 Hz. A routine developed in MatLab (The MathWorks, Inc., Natick, MA, USA) was used to identify the presence of hip muscle contraction after each repetition. Repetitions were excluded if the EMG signal of any of the muscles was equal to or greater than the signal at rest plus two standard deviations, which would be considered muscle contraction²⁶.



Figure 1. Positioning of the subject on the isokinetic dynamometer.

During the execution of the test, the isokinetic dynamometer recorded the resistance torque at each point throughout the range of hip medial rotation, without discriminating the torques generated by joint, connective, and muscle tissues from those produced by the weights of the leg, foot, and lever arm. The resulting passive torque curve was later used to calculate the stiffness and mean passive torque. The test-retest reliability of this measurement was analyzed in a previous study, showing excellent Intraclass Correlation Coefficient (ICC=0.92)²⁶.

Measurement of lateral rotator concentric torque

The force of the lateral rotators was indexed in the present study as its maximal capacity to generate concentric torque. This measurement was selected due to its connection with the muscle's CSA²⁷. The lateral rotator concentric force test was performed in the same position as the passive resistance torque assessment. The range of motion was from 40° of medial rotation to 25° of lateral rotation at a constant speed of 60°/s. This speed is indicated when the purpose is to capture the maximal capacity of torque generation²⁸.

Initially, a submaximal test of three hip rotation repetitions was performed to familiarize the subject with the procedure. Hereafter, the subject performed three rotation repetitions at maximal strength, with 60-second intervals between trials. The participant was instructed to execute maximal strength in the direction of hip lateral rotation, receiving verbal encouragement.

Finally, one repetition was performed with the lever arm in isolation at the speeds of 5°/s and 60°/s to obtain the torque generated by the lever arm in the passive and active tests, respectively. Peak torque and work measurements of the lateral rotators showed excellent test-retest reliability in a pilot study, showing ICC of 0.97 and standard error measurement (SEM) of 3.07 for peak torque and ICC of 0.98 and SEM of 2.31 for work.

Data reduction

The data for passive resistance torque during medial rotation and lateral rotator concentric torque were obtained through the dynamometer's software (Biodex Medical Systems, Inc.). Hip joint passive stiffness was calculated with the mean inclination (first derivative) of the passive torque curve within the range of motion of 0 to 20° of medial rotation. This range was used because it is the range required in most functional activities that involve the lower limbs²⁹. The routine calculated the first

derivative of the curve at every 0.05° and, then, considered the average of all values in the 20° range. The average of the stiffness values obtained in the three repetitions of the test was used for the analysis.

The lateral rotator peak torque and work was calculated considering a range of 35° of medial rotation to 20° of lateral rotation. Peak torque corresponded to the highest torque recorded during the range of motion, whereas work was calculated as the total area under the concentric torque curve as a function of joint displacement throughout the range of motion. For the analysis, we used the average peak torque and muscle work obtained from three repetitions.

The torque generated by the weight of leg and foot segments and by the lever arm were subtracted from the total torque recorded by the dynamometer for the calculation of all the variables. The predicted mass of the body segments and the distance from the center of mass to the axis of joint rotation were obtained according to Dempster's anthropometric table²³. Next, trigonometric calculations were used to determine the torque generated by these segments in each joint position.

Statistical analysis

Descriptive statistics were used to characterize the sample through the calculation of the mean, standard deviation, and minimal and maximal values of the variables passive stiffness, passive torque, peak torque, and work. All variables showed normal distribution according to the Kolmogorov-Smirnov test. Simple linear regression analysis was used to investigate the association between hip stiffness during medial rotation and the following variables: lateral rotator peak torque and work. All analyses were carried out in the software Statistical Package for the Social Sciences (SPSS), version 15.0, with a significance level of $\alpha=0.05$.

Results

The values for hip passive stiffness during medial rotation and lateral rotator peak torque and work are described on Table 2. Simple linear regression analysis showed a correlation of $r=0.707$ ($R^2=0.501$); $p<0.001$ between hip passive stiffness during medial rotation and lateral rotator peak torque (Figure 2). The correlation between hip stiffness and lateral rotator work was $r=0.769$ ($R^2=0.591$); $p<0.001$ (Figure 3).

Table 2. Values of hip passive stiffness during medial rotation and values of hip lateral rotators peak torque and work (n=26).

	Mean (Standard Deviation)	Minimum values	Maximum values
Stiffness (Nm/rad)	10.10 (3.85)	5.47	17.51
Peak Torque (Nm)	31.26 (12.69)	11.26	58.90
Work (J)	22.85 (10.17)	7.52	40.99

Nm/rad=Newton-meter per radian; Nm=Newton-meter; J=Joule.

Discussion

The results obtained in the present study showed a moderate to good association²⁸ between hip passive stiffness and isokinetic variables related to the performance of hip lateral rotators. According to Portney and Watkins³⁰, an association with the value of r between 0 and 0.25 indicates a weak correlation or absence of correlation; between 0.25 and 0.50, a weak correlation; between 0.50 and 0.75, a moderate to good correlation; and above 0.75, an excellent correlation. The coefficients of determination showed that 50 to 59% of the variability of the measurement of hip stiffness is explained by the performance of the lateral rotators of this joint. The association between these two variables is probably due to muscle trophism, because this is the main factor exerting influence both on active torque and passive stiffness^{19,20,27,31}. Thus, a hip joint with more trophism from the lateral rotators tends to have more force of this muscle group and more stiffness during medial rotation. However, experimental studies are needed to confirm this hypothesis.

Previous studies have already shown the relationship between passive stiffness and the ability to produce torque in other joints³²⁻³⁴. Klinge et al.³² found that isometric strengthening of the hamstrings increased the torque produced by these muscles, with a concomitant increase in passive stiffness during knee extension. Ocarino et al.³³ showed that strengthening the elbow flexors increased the passive stiffness of this joint. Moreover, in a cross-sectional study, Gajdosik³⁴ found moderate correlation coefficients (values between 0.50 and 0.56) between plantar flexor concentric torque and ankle stiffness during dorsiflexion. These correlation coefficients are lower than those of the present study. Such difference could be explained by the greater trophism of the hip muscles³⁵ in comparison to the ankle³⁶. It is possible that the passive stiffness of the hip joint is more dependent on muscle volume than that of the ankle, which is more influenced by capsule, tendons, and ligaments. Moreover, the mean age of the participants of the present study was lower than the age of the participants of the

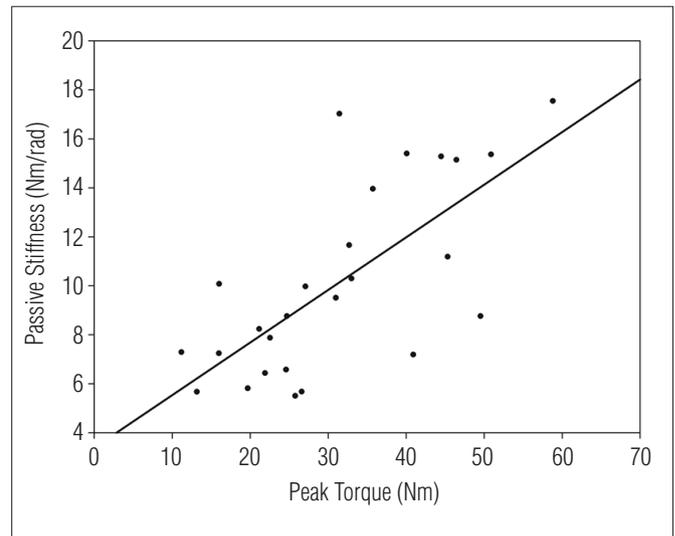


Figure 2. Linear regressions between hip passive stiffness during medial rotation and lateral rotator peak torque ($R^2=0.501$; $p<0.0001$).

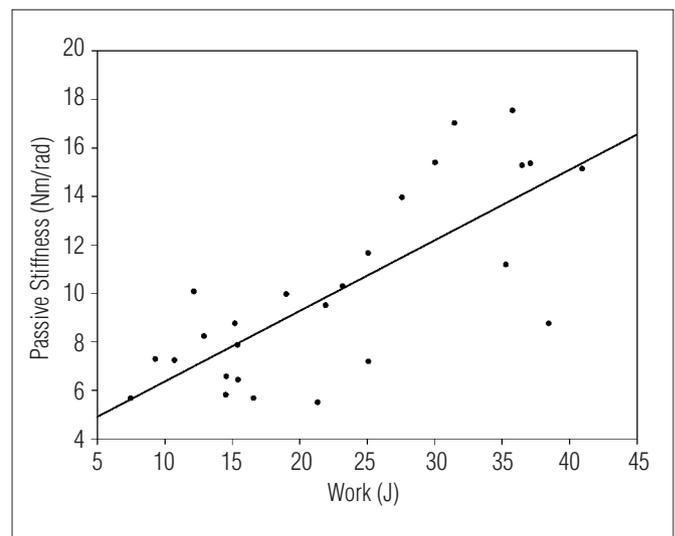


Figure 3. Linear regressions between hip passive stiffness during medial rotation and lateral rotator work ($R^2=0.591$; $p<0.0001$).

study by Gajdosik³⁴, which included elderly subjects in its sample. This age group has reduced muscle trophism as a consequence of the process of sarcopenia, a very common condition in those above 65 years of age³⁷. This fact can influence the association between the variables stiffness and muscle torque. Finally, the sample of the study by Gajdosik³⁴ was composed solely by women, which can also modify the association between these variables, since women's muscle has a smaller CSA³⁸. Thus, the strength of the association between passive stiffness and muscle torque can be dependent on factors such as the joint analyzed, age, and sex.

In the present study, we found a greater association between hip stiffness and work than between stiffness and peak torque of the lateral rotators ($r=0.769$ and 0.707 , respectively). Muscle work is a variable that provides the torque generated by the muscle group in its entire range of motion. Peak torque, however, represents the maximal torque produced at a specific point of the range of motion. Thus, it is possible that muscle work is a variable that better represents the total torque-generating capacity of a certain muscle group, which could justify these data.

During a maximal voluntary contraction, the torque generated by the muscles during the movement corresponds to the sum of the passive and active torques⁷. This study aimed to analyze the correlation between stiffness, a property related to passive torque, and the concentric torque of the lateral rotators. Initially, passive stiffness could be embedded in the values of concentric torque, favoring the existence of a correlation between the variables. However, it was observed that the mean passive torque generated by the hip joint during medial rotation is considerably lower than the values of lateral rotator concentric torque, evidencing the low contribution of passive torque to the generation of concentric strength. Mean passive torque during medial rotation of the sample was of 2.39 Nm, while the mean of the torque generated during the lateral rotator force test was 24.21 Nm. Thus, it is unlikely that the passive torque that is present in the lateral rotator peak torque and work have separately favored the occurrence of the correlations reported in the present study. Such contribution might have been more significant if measures of eccentric torque had been used.

Although a considerable part of hip stiffness is explained by muscle strength, other factors can exert influence over this property. There is an inverse relationship between passive stiffness and muscle flexibility³⁹⁻⁴¹, i.e. the greater the flexibility of the tissue, the lesser the stiffness. This relationship has yet to be investigated in the hip, however it is possible that the flexibility of the muscles around this joint has some influence on its stiffness. Other factors responsible for the passive stiffness of a joint are structures such as capsule and ligaments, which also go undetected in the force assessment but, in the hip joint, can exert relatively less influence given the great muscle volume present in this joint, as previously discussed.

Modifications in the alignment of the femoral neck modify the range of medial or lateral rotation available in the hip joint⁴². The excessive anteversion of the femoral head is associated with greater range of hip internal rotation during gait⁴³, which can promote an increase in the

length of the tissues in the posterior region of this joint, resulting in lower stiffness. Thus, the alignment of the femoral neck is another possible factor that can influence the relationship between strength and stiffness.

Finally, neuromuscular factors⁴⁴⁻⁴⁶ (e.g. recruitment of motor units⁴⁵ and coordination among agonist and antagonist muscles⁴⁶) may have contributed to the reduction in the strength of association between the variables concentric torque and passive stiffness in the hip joint. These factors affect the torque-generating capacity without affecting the passive properties of the joint. Thus, intervention with the purpose to increase passive stiffness must prioritize muscle hypertrophy. It has been shown that, in the initial stages of strength training, the gain in force occurs through neural mechanisms, and that muscle hypertrophy occurs only after six weeks of training⁴⁴. Therefore, it is expected that the gain in stiffness during one intervention with muscle strengthening occurs after this period. Programs that focus on the gain in CSA must prioritize moderate loads (70-85% of maximal repetition), sets with 8 to 12 repetitions performed two or three times a week⁴⁷. In addition, studies suggest that eccentric strength training at high velocities can be used to prioritize hypertrophy²², and thus, the gain in passive stiffness, possibly being an option of intervention for subjects in more advanced stages of training.

The results of the present study are limited to young subjects without neurological alterations. Elderly subjects or those with neurological injuries may show behaviors different from the ones reported in the present study regarding passive stiffness and the torque-generation capacity, which can modify the association between these variables. Note also that the correlational design of the study does not allow the determination of a cause-and-effect relationship between the variables, which should be investigated in further studies. Furthermore, the present study did not investigate the other factors that can influence the relationship between stiffness and hip muscle force, such as muscle flexibility, alignment of the femoral neck, and neuromuscular factors that affect force generation. In clinical practice, the investigation of hip passive stiffness must be performed in conjunction with other clinical tests because the kinematic changes associated with injuries have multifactorial characteristics, and hip stiffness alone becomes insufficient to the understanding of these changes.

The present study showed moderate to good correlation between passive stiffness of the hip during the motion of medial rotation and the concentric torque of the lateral rotators of this joint. In this way, individuals with reduced lateral rotator

force may have low levels of passive stiffness during medial rotation and may require an intervention to promote gains in this component. Based on the results of this study, it is possible to speculate that lateral rotator strength training leads to increased hip joint stiffness during medial rotation. However, experimental studies are needed to provide conclusive data.

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