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Validity and reliability of clinical tests for assessing hip passive stiffness

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ABSTRACT

Inadequate levels of hip passive joint stiffness have been associated with the occurrence of movement dysfunction, development of pathologies and reduction in performance. Clinical tests, designed to evaluate hip joint stiffness, may allow the identification of improper stiffness levels. The purpose of this study was to determine the concurrent validity as well as the intra- and inter-examiners reliabilities of clinical measures used to assess hip passive stiffness during internal rotation. Fifteen healthy participants were subjected to test-retest evaluations by two examiners. Two clinical measures were performed: 'position of first detectable resistance' and 'change in passive resistance torque'. The results of these tests were compared to the passive stiffness measured with an isokinetic dynamometer (gold standard measure). A significant correlation was found between the stiffness measured with the isokinetic dynamometer and the clinical measures of 'position of first detectable resistance' ($r = -0.85$ to -0.86, $p < 0.001$) and 'change in passive resistance torque' ($r = 0.78$ to 0.84, $p \leq 0.001$). The Intraclass Correlation Coefficients for intra- and inter-examiners reliabilities varied from 0.95 to 0.99. Thus, the results demonstrated that the clinical measures have adequate validity and reliability for obtaining information on hip passive stiffness during internal rotation.

1. Introduction

Joint stiffness is a mechanical property represented by the change of the increasing resistance torque exerted by a joint, when it is moved by internal or external torques (Latash and Zatsiorsky, 1993). This property is influenced both by muscle contraction and the passive stiffness of muscles and other structures surrounding a joint (Latash and Zatsiorsky, 1993; Obusek et al., 1995). Depending on the magnitude of joint stiffness demanded by a motor task, passive mechanisms may be sufficient to resist an undesirable movement or to maintain a given posture (Loram et al., 2007). When muscle contraction is needed to produce greater amounts of joint stiffness, passive and active stiffnesses are complementary (Salsich and Mueller, 2000; Moritz and Farley, 2004). Hence, the contribution of the passive components to joint stiffness plays a crucial role on how resistance to joint movement takes place with as little muscular activity as possible (Gleim et al., 1990; Loram et al., 2007).

There are movement patterns of walking, running and jumping that may be influenced by the level of hip joint stiffness (Melamed and Hutchinson, 2002; Fonseca et al., 2007). The presence of low hip stiffness in the transverse plane may result in the occurrence of excessive amount and/or duration of hip internal rotation (IR) and foot pronation during the stance phase of gait (Fonseca et al., 2007). These movement patterns have been associated with the development of conditions such as low back pain (Botte, 1981), patellofemoral syndrome (Tiberio, 1987; Barton et al., 2009) and medial tibial stress syndrome (Bennett et al., 2001; Willems et al., 2007). Conversely, excessive hip joint stiffness may limit lower-limb IR and foot pronation, compromising the absorption and dissipation of mechanical energy (Williams et al., 2004; Fonseca et al., 2007). In this case, part of the energy that should be dissipated at the foot-ankle complex would be transferred to other structures, predisposing them to injury development (Williams et al., 2001; Butler et al., 2003; Fonseca et al., 2007). Williams et al. (2001) have reported that runners with excessive stiffness of the lower limbs show higher incidence of stress fractures than those with low levels of stiffness. Therefore, the tissues surrounding the hip joint must have adequate stiffness to generate appropriate resistance to IR.

The existence of methods that investigate hip passive stiffness may be clinically useful. The measure of joint passive stiffness can be obtained by using an isokinetic dynamometer, the gold standard instrument for this measure (Chesworth et al., 1991). Despite its wide use in research (Porter et al., 2002; Vaz et al., 2008), it is not

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available for the majority of clinicians. Further, although there are clinical measures that assess the passive stiffness of other joints (Lin and Yang, 2006; Gombatto et al., 2008), there is a lack of methods developed to clinically evaluate hip IR passive stiffness.

A possible way of obtaining information on the passive stiffness of a joint could be by determining the angle at which the first resistance to a specific external torque can be clinically detected (Latash and Zatsiorsky, 1993). This angle may be called 'position of first detectable resistance'. Another option may be by measuring the magnitude of the increase in the passive resistance torque when a joint is moved within a determined range of motion. This measure could be called 'change in passive resistance torque'. To use these measures in clinical practice, it is necessary to assess their validity and reliability (Portney and Watkins, 2000; Gadotti et al., 2006). Therefore, the purpose of this study was to determine the concurrent validity as well as the intra- and inter-examiners reliabilities of the measurements 'position of first detectable resistance' and 'change in passive resistance torque', applied to assess hip IR passive stiffness.

Fig. 1. Hip passive stiffness measured with an isokinetic dynamometer.

2. Methods

2.1. Subjects

Fifteen young healthy subjects (six males and nine females; mean age of 24.8 ± 4.2 years; mean body mass of 59.7 ± 8.4 kg; mean height of 1.7 ± 0.1 m and mean Body Mass Index of 21.1 ± 1.9 kg/m^2) volunteered to participate in this study. The sample size was determined based on data of a pilot study conducted with seven participants that performed the same procedures of the main study. The coefficient of the correlation between the gold standard measure and the clinical tests, obtained in this pilot study, was used to establish the sample size of the main study, considering a statistical power of 90% and a significance level of 0.05 (Cohen, 1988; Portney and Watkins, 2000). The inclusion criteria were: absence of symptoms or history of injuries in the lower limbs, and a minimum range of motion (ROM) of 20° of hip IR. The exclusion criterion was participants' inability to keep their hip muscles relaxed. The participants signed an informed consent and the institution's Ethics in Research Committee approved the study procedures.

2.2. Procedures

Initially, body mass, height, and shank and foot lengths of the dominant limb of each subject were measured in accordance with Dempster's anatomical references (Winter, 1990). The dominant limb was defined as the lower limb with which a participant would kick a ball as far as possible.

2.2.1. Passive stiffness measured by isokinetic dynamometry

The passive resistance torque (PRT) produced at the hip joint during IR was measured with an isokinetic dynamometer (Biodex System 3 Pro, Shirley, USA). This measure was carried out with the subject lying prone, the knee of the dominant limb positioned at 90° of flexion, the tibial tuberosity aligned with the axis of rotation of the equipment and the pelvis stabilized with velcro® straps (Fig. 1). The hip was passively moved from 5° of external rotation to 20° of IR, with a constant velocity of 5°/s. For data reduction, the first 15° of IR (from 0°) was chosen since this is a range of motion involved in many daily functional activities (Levens et al., 1948; Perry, 1992). The neutral position of the hip (0°) was the position where the anterior border of tibia was vertical, measured with an analog inclinometer. The subject was asked not to resist or help voluntarily the motion of the equipment's lever-arm. Five repetitions were conducted to allow tissue viscoelastic accommodation. Three repetitions were carried out and an additional repetition was performed without the participant, in order to register the torque generated only by the weight of the equipment's lever-arm.

Surface electromyography of gluteus maximus, tensor fascia lata and biceps femoris was monitored to guarantee that these muscles were relaxed. After shaving and cleaning the skin, active electrodes were attached to the belly of each muscle (Cram et al., 1998). The electromyographic signals were initially registered with the subject completely relaxed. After each repetition, data were processed with a custom Matlab program (The Mathworks Inc.), which enabled the identification of contractions of each muscle, defined as activity amplitudes equal to or greater than two standard deviations of the signal of the same muscle relaxed (Lamontagne et al., 1997). Repetitions with muscle contractions were rejected and a new repetition was carried out. These data were measured with the MP100 system (Biopac System, Goleta, USA), at a frequency of 1000 Hz, and band-pass filtered with cut-off frequencies of 10 Hz and 500 Hz.

The isokinetic dynamometer data were processed using the software Matlab, which calculated the passive stiffness. These data were filtered using a fourth-order low-pass filter (Butterworth), with a cut-off frequency of 1.25 Hz. The torque was corrected for the torques generated by the weight of the lever-arm. The torque was further corrected by the torque produced by the weight of the shank and foot, calculated based on anthropometric data (Winter, 1990). The resultant torque of each repetition was graphically demonstrated in a torque-angle curve (Fig. 2). Stiffness was calculated as the mean slope (first derivative) of the torque-angle curve at the first 15° of hip IR, in Nm/rad. The mean slope of each repetition was defined as the mean value of the multiple slopes obtained between each two subsequent points of the torque-angle curve (Bressel et al., 2004), at intervals of 0.05°. Although determining the slope based only in the torques generated at 0° and 15° would probably provide values similar to those obtained in this study, the mean value of multiple slopes between 0° and 15° was calculated in order to consider the nonlinearities and irregularities of the torque-angle curves (McFaull and Lamontagne, 1998; Souza et al., 2009). The final value of stiffness for each participant was calculated as the mean value obtained from the three test

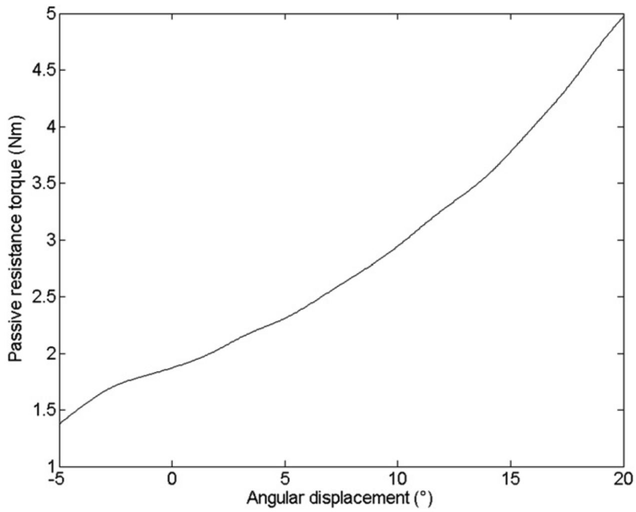

Fig. 2. Torque-angle curve (absolute values) of a representative subject, obtained in one repetition of the test with the isokinetic dynamometer.

repetitions. Finally, these values were used to calculate the correlations with the results of the clinical measures.

Test-retest reliability of hip stiffness measured with the isokinetic dynamometer was determined in the above-mentioned pilot study. The measure was carried out in two distinct days, with a one-week interval. The Intraclass Correlation Coefficient ($ICC_{3,3}$) obtained was 0.92.

2.2.2. Clinical measures for assessing passive stiffness of the hip

Two previously trained examiners applied the clinical measures proposed to generate information on hip IR passive stiffness. Both measures were carried out in two occasions, with a one-week interval. Each examiner was blind for the results obtained by the other and for the results of the isokinetic dynamometry. During the clinical measurements, the participants were required to stay relaxed. If the examiner perceived any muscle contraction sign (visually or by palpation), the test was repeated. Before these measurements, each examiner moved manually the participant's hip into IR, five times, in order to allow tissue viscoelastic accommodation.

2.2.2.1. Position of first detectable resistance. The subject was positioned lying prone on a table with the pelvis stabilized by velcro® straps, in a similar position of the test performed with the isokinetic dynamometer (Fig. 3). The examiner allowed passive hip IR, produced by the shank weight, to occur until the tension of the hip passive structures stopped this movement. The examiner should support the participant's shank to maintain the knee in 90° of flexion, but should not apply any force to limit or favor the hip IR movement. Thus, the 'position of first detectable resistance' was defined as the joint position in which the torque produced by the shank and foot weights became equal to the passive resistance torque generated by the hip during IR. This position was measured using an inclinometer placed on the anterior border of the tibia, 5 cm distal from tibial tuberosity. The greater the hip stiffness, the smaller was the IR angle at which the examiner could identify the first resistance to motion. This measurement was carried out three times. The final value was calculated as the mean value of the results obtained in the three repetitions, in degrees.

2.2.2.2. Change in passive resistance torque. The objective of this measurement was to estimate the magnitude of the increase in the PRT when the hip was moved within a specific IR range of

Fig. 3. Measure of 'position of first detectable resistance' of the hip joint.

motion. The difference between the resistance forces against IR, produced passively by the hip in two joint positions, was measured using a hand-held dynamometer at the low threshold (MICROFET 2, Draper, USA). The dynamometer was placed 35 cm distal to the femur medial epicondyle, and the examiner manually moved the participant's hip into IR by applying a force perpendicular to the shank, while the participant remained sitting (Fig. 4). Since the hand-held dynamometer, in general, does not register the resistance force at 0° of hip rotation, the first measure of resistance force was taken at 5° of hip IR for all participants. The second resistance force was registered with the hip positioned at 20° of IR to maintain the same range of motion of the isokinetic dynamometer measurements. It was hypothesized that the stiffness obtained between 0° and 15° of IR (measured by the isokinetic dynamometer) would be similar and comparable to the stiffness registered between 5° and 20°, since both are measured at initial ranges of IR. In order to measure the hip angles, the inclinometer was placed on the anterior border of the tibia (5 cm

Fig. 4. Measure of 'change in passive resistance torque' of the hip joint.

Table 1
Means, standard deviations (SD), intraclass correlation coefficients (ICC) and standard errors of measurement (SEM) for the clinical measures of 'position of first detectable resistance' and 'change in passive resistance torque' of the hip joint.

	Position of first detectable resistance		Change in passive resistance torque	
	Mean (°/kg)	SD (°/kg)	Mean (Nm/kg)	SD (Nm/kg)
E1(1)	0.54	0.32	0.08	0.05
E1(2)	0.56	0.32	0.08	0.04
E2(1)	0.56	0.32	0.09	0.04
E2(2)	0.59	0.31	0.09	0.04
	ICC	(1.96)SEM	ICC	(1.96)SEM
E1(1) × E1(2)	0.99	0.06	0.95	0.02
E2(1) × E2(2)	0.99	0.06	0.97	0.01
E1(1) × E2(1)	0.99	0.05	0.95	0.02
E1(2) × E2(2)	0.99	0.07	0.97	0.01

– Positive angle values indicate positions of hip internal rotation. Positive torque values indicate resistance to internal rotation of the hip joint.
– E1, examiner one; E2, examiner two.
– (1), test; (2), retest.

distal to tibial tuberosity). The neutral position of the hip was defined as the position in which the anterior border of tibia was vertical. This measurement was conducted five times.

The forces registered by the hand-held dynamometer were multiplied by the measurement lever-arm (35 cm) to obtain the PRT values. The largest and smallest PRT values registered in each IR position were rejected and the mean of the three other values was calculated in Newton-meters (Nm). Subsequently, the difference between the PRTs generated at 20° and 5° of hip IR was determined. Since the angular displacements were equal for all participants, the change in torque did not need to be divided by the range of motion (which would be necessary to have a stiffness estimate, in Nm per degrees).

The results of both clinical tests were normalized by the body mass of each participant in order to reduce the influence of shank weight on the measures. This simple normalization was chosen due to the clinical and practical nature of the measure, considering the total body mass as proportional to the shank mass (Winter, 1990).

2.3. Statistical analyses

The degree of agreement between the results obtained with the clinical measures and the passive stiffness values measured with the isokinetic dynamometer was quantified by calculating the Pearson's correlation coefficient, considering a significance level of 0.05. In this analysis, the mean of the results obtained in the first and second evaluation days, for each examiner, were used. The intra- and inter-examiners reliabilities were determined by calculating the $ICC_{3,3}$. In addition, the Standard Error of Measurement (SEM) of each clinical test was calculated.

3. Results

The mean value of hip passive stiffness measured with the isokinetic dynamometer was 5.61 (±5.35) Nm/rad. The means and standard deviations from both clinical measures are presented in Table 1. The Pearson's coefficients obtained from the first examiner data were $r = -0.85$ ($p < 0.001$) and $r = 0.84$ ($p < 0.001$) for the correlation between the hip passive stiffness measured with the isokinetic dynamometer and the results of the clinical measures 'position of first detectable resistance' and 'change in passive resistance torque', respectively (Fig. 5). For the second examiner, these correlation coefficients were $r = -0.86$ ($p < 0.001$) and $r = 0.78$ ($p = 0.001$). ICCs varied from 0.95 to 0.99 for the intra- and inter-reliabilities for both clinical measures. The ICC values and SEMs are shown in Table 1.

4. Discussion

The results of this study demonstrated that the clinical measures show a significant correlation with the gold standard measurement of hip stiffness. Portney and Watkins (2000) suggest that correlation coefficients above 0.75 are considered good to excellent. Furthermore, studies that investigated the concurrent validity of clinical measures and found correlation coefficients that varied from 0.57 to 0.78 considered these measures adequate to be used in the clinical practice (Baraúna et al., 2005; McEwan et al., 2007; McKenna et al., 2009). The ICC values found in the present study (above 0.90) are indicative of excellent intra- and inter-examiners reliabilities (Portney and Watkins, 2000). Therefore, the values of correlation coefficient and ICC found in this study indicate that the proposed clinical measures have adequate validity and reliability for obtaining information on hip IR passive stiffness.

The measure 'change in passive resistance torque' showed smaller correlation coefficients than the measure 'position of first detectable resistance'. This fact may be explained by the different sagittal hip positions used in the measurements conducted with

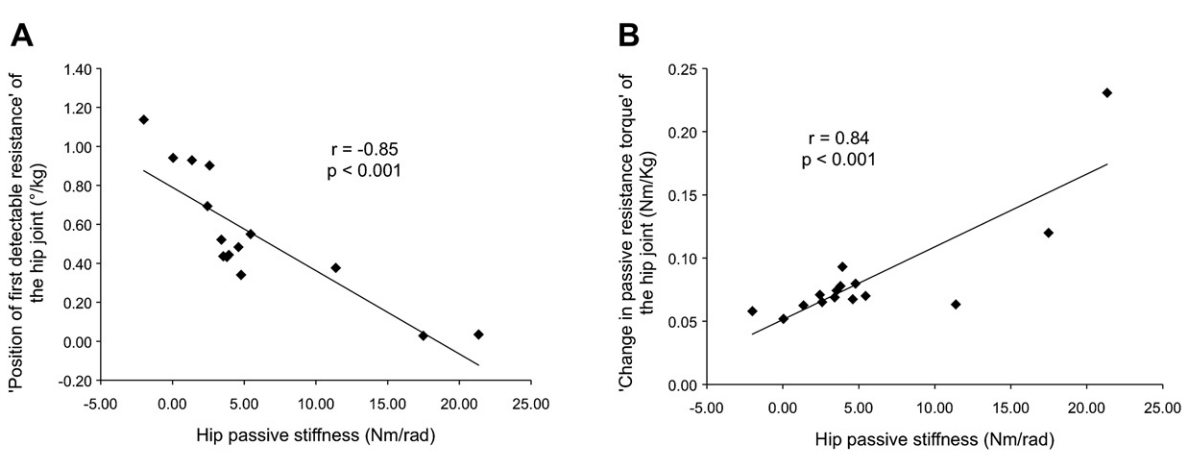

Fig. 5. Scatter plots of the association between the hip passive stiffness measured with an isokinetic dynamometer and: (A) 'position of first detectable resistance' of the hip joint; (B) 'change in passive resistance torque' of the hip joint.

the isokinetic dynamometer (0° of hip flexion) and with the hand-held dynamometer (90° of hip flexion). We opted for positioning the individuals seated since when the subject is lying prone with knee positioned at 90° of flexion, the gravity produced hip IR, which prevents the use of the hand-held dynamometer to measure hip resistance to IR. Furthermore, a pilot study revealed that the seated position was easier for the participants to keep their muscle relaxed than in lying supine with knee flexion of 90°.

A property frequently used to infer about passive stiffness is muscle flexibility (Aquino et al., 2006). However, some studies have demonstrated that less than 30% of the variability found in the stiffness measure may be accounted for flexibility (Wilson et al., 1991; Aquino et al., 2006). Moreover, the measurement of flexibility is not determined only by mechanical properties but also by individual's stretch tolerance (Magnusson et al., 1996). The measurement of hip passive stiffness may provide more relevant information about joint mechanics than flexibility measurement (Wilson et al., 1991; Gleim and McHugh, 1997). Therefore, although therapists might think intuitively that joint stiffness could be inferred directly from some measure of flexibility, this would be a mistake. The measures proposed in this study are more related to the resistance torque developed by the joint tissues than to the available ROM (measure of flexibility). The two methods we have developed carefully considered the lack of relationship between simple tests of joint ROM and stiffness to clinically establish a useful and valid measure of joint stiffness.

The clinical tests may help therapists in their clinical practice; however, some limitations have to be identified. The proposed tests are not applicable to individuals with pain during test execution, as they could not be able to keep their muscles relaxed. Nevertheless, it should be noted that some pathological conditions at joints other than the hip (e.g., foot-ankle complex), which might be related to abnormal hip stiffness (Willems et al., 2007), may not affect hip muscles activity during test execution. In these cases, the clinical measures could be used. One of the inclusion criteria established in this study was a minimum range of 20° of hip IR. This criterion implies that the tests are not applicable to individuals that have limited flexibility of hip IR. Finally, smaller values of correlation coefficient and ICC are expected if the tests were applied by examiners without previous training. The period for training the examiners of this study was two weeks.

Another limitation is that the results of the study does not inform about the measures' responsiveness for clinical changes. Experimental studies with interventions designed to modify joint stiffness are necessary for this purpose. Our study did not aim to classify the estimated hip stiffness values as low, normal and high. Classification estimates can be generated by future studies on the relationship of these measures' results with pathologic conditions and/or movement patterns. Moreover, the participants of this study presented Body Mass Index below 27 kg/m^2 and this fact restrains the results generalization for the whole population.

To date, the investigation of hip passive stiffness has been possible only with the use of isokinetic dynamometers. The present study developed simple and valid measures to evaluate this property in clinical practice. The proposed tests are recommended to evaluate hip passive stiffness in individuals without hip pain that are capable to keep their muscles relaxed during the tests execution. The tests may enable therapists to investigate possible between-limbs asymmetries of hip stiffness and associate the measures' values with the presence of pathologic conditions and/or altered movement patterns. Furthermore, it is worth noting the applicability of the tests in preventive contexts. They can be used to identify individuals that could benefit from interventions intended to modify stiffness in order to prevent injuries related to inadequate levels of hip stiffness.

5. Conclusion

The proposed clinical measures are valid and reliable and can be used to obtain information on the passive stiffness of the hip during IR. The use of the 'position of first detectable resistance' is considered more practical than the use of 'change in passive resistance torque' since the former requires more accessible and easy-to-use equipment.

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References

Aquino C, Gonçalves GGP, Fonseca S, Mancini MC. Análise da relação entre flexibilidade e rigidez passiva dos isquiostibiais. Revista Brasileira de Medicina do Esporte 2006;12(4):195–200.

Baraúna MA, Canto RST, Sanchez HM, Bustamante JCF, Ventura-Silva RA, Malusá S. Validade e confiabilidade intra-indivíduo do cifolordômetro na avaliação da convexidade torácica. Brazilian Journal of Physical Therapy 2005;9(3):319–25.

Barton CJ, Levinger P, Menz HB, Webster KE. Kinematic gait characteristics associated with patellofemoral pain syndrome: a systematic review. Gait and Posture 2009;30(4):405–16.

Bennett JE, Reinking MF, Pluemer B, Pentel A, Seaton M, Killian C. Factors contributing to the development of medial tibial stress syndrome in high school runners. Journal of Orthopaedic & Sports Physical Therapy 2001;31(9):504–10.

Botte RR. An interpretation of the pronation syndrome and foot types of patients with low back pain. Journal of the American Podiatric Medical Association 1981;71(5):243–53.

Bressel E, Larsen BT, McNair PJ, Cronin J. Ankle joint proprioception and passive mechanical properties of the calf muscles after an Achilles tendon rupture: a comparison with matched controls. Clinical Biomechanics (Bristol, Avon) 2004;19(3):284–91.

Butler RJ, Crowell III HP, Davis IM. Lower extremity stiffness: implications for performance and injury. Clinical Biomechanics (Bristol, Avon) 2003;18 (6):511–7.

Chesworth BM, Vandervoort AA, Koval JJ. A pilot study to compare the subjective and objective evaluation of passive ankle joint stiffness. Physiotherapy Canada; 1991:4313–8.

Cohen J. The significance of a product moment r_s. In: Cohen J, editor. Statistical power analysis for the behavioral sciences. New York, USA: Lawrence Erlbaum Associates; 1988. p. 75–107.

Cram JR, Kasman GS, Holtz J. Instrumentation. In: Cram JR, Kasman GS, Holtz J, editors. Introduction to surface eletromyography. Gaithersburg: Aspen Publishers, Inc.; 1998. p. 45–80.

Fonseca ST, Ocarino JM, Silva PLP, Aquino CF. Integration of stress and their relationship to the kinetic chain. In: Magee DJ, Zachazewski JE, Quillen WS, editors. Scientific foundations and principles of practice in musculoskeletal rehabilitation. St Louis: Saunders Elsevier; 2007. p. 476–86.

Gadotti IC, Vieira ER, Magee DJ. Importance of clarification of measurements properties in rehabilitation. Brazilian Journal of Physical Therapy 2006;10 (2):137–46.

Gleim GW, McHugh MP. Flexibility and its effects on sports injury and performance. Sports Medicine 1997;24(5):289–99.

Gleim GW, Stachenfeld NS, Nicholas JA. The influence of flexibility on the economy of walking and jogging. Journal of Orthopaedic Research 1990;8(6):814–23.

Gombatto SP, Klaesner JW, Norton BJ, Minor SD, Van Dillen LR. Validity and reliability of a system to measure passive tissue characteristics of the lumbar region during trunk lateral bending in people with and people without low back pain. Journal of Rehabilitation Research and Development 2008;45(9):1415–29.

Lamontagne A, Malouin F, Richards CL, Dumas F. Impaired viscoelastic behaviour of spastic plantarflexors during passive stretch at different velocities. Clinical Biomechanics (Bristol, Avon) 1997;12(7, 8):508–15.

Latash ML, Zatsiorsky VM. Joint stiffness: myth or reality? Human Movement Science 1993;12(6):653–92.

Levens AS, Inman VT, Blosser JA. Transverse rotation of the segments of the lower extremity in locomotion. The Journal of Bone and Joint Surgery 1948;30A (4):859–70.

Lin JJ, Yang JL. Reliability and validity of shoulder tightness measurement in patients with stiff shoulders. Manual Therapy 2006;11(2):146–52.

Loram ID, Maganaris CN, Lakie M. The passive human calf muscles in relation to standing: the non-linear decrease from short range to long range stiffness. The Journal of Physiology 2007;584(Pt 2):661–75.

Magnusson SP, Simonsen EB, Aagaard P, Sorensen H, Kjaer M. A mechanism for altered flexibility in human skeletal muscle. The Journal of Physiology 1996;497 (Pt 1):291–8.
McEwan I, Herrington L, Thom J. The validity of clinical measures of patella position. Manual Therapy 2007;12(3):226–30.
McFaull SR, Lamontagne M. In vivo measurement of the passive viscoelastic properties of the human knee joint. Human Movement Science 1998;17: 139–65.
McKenna L, Straker L, Smith A. The validity and intra-tester reliability of a clinical measure of humeral head position. Manual Therapy 2009;14(4):397–403.
Melamed H, Hutchinson M. Soft tissue problems of the hip athletes. Sports Medicine & Arthroscopy 2002;2(2):168–75.
Moritz CT, Farley CT. Passive dynamics change leg mechanics for an unexpected surface during human hopping. Journal of Applied Physiology 2004;97 (4):1313–22.
Obusek JP, Holt KG, Rosenstein RM. The hybrid mass-spring pendulum model of human leg swinging: stiffness in the control of cycle period. Biological Cybernetic 1995;73(2):139–47.
Perry J. Gait analysis: normal and pathological function. New Jersey: Slack, Inc.; 1992. p. 111–30.
Porter MM, Anderson M, Hellstrom U, Miller M. Passive resistive torque of the plantar flexors following eccentric loading as assessed by isokinetic dynamometry. Canadian Journal of Applied Physiology 2002;27(6):612–6.
Portney LG, Watkins MP. Foundations of clinical research: application to practice. New Jersey: Prentice Hall Health; 2000.
Salsich GB, Mueller MJ. Effect of plantar flexor muscle stiffness on selected gait characteristics. Gait and Posture 2000;11(3):207–16.
Souza TR, Fonseca ST, Goncalves GG, Ocarino JM, Mancini MC. Prestress revealed by passive co-tension at the ankle joint. Journal of Biomechanics 2009;42(14):2374–80.
Tiberio D. The effect of excessive subtalar joint pronation on patellofemoral mechanics: a theoretical model. Journal of Orthopaedic & Sports Physical Therapy 1987;9(4):160–5.
Vaz DV, Mancini MC, Fonseca ST, Arantes NF, Pinto TPS, Araújo PAA. Effects of strength training aided by electrical stimulation on wrist muscle characteristics and hand function of children with hemiplegic cerebral palsy. Physical & Occupational Therapy in Pediatrics 2008;28(4):309–25.
Willems TM, Witvrouw E, De CA, De CD. Gait-related risk factors for exercise-related lower-leg pain during shod running. Medicine & Science in Sports & Exercise 2007;39(2):330–9.
Williams III DS, Davis IM, Scholz JP, Hamil K, Buchanan TS. High-arched runners exhibit increased leg stiffness compared to low-arched runners. Gait and Posture 2004;19:263–9.
Williams III DS, McClay IS, Hamill J. Arch structure and injury patterns in runners. Clinical Biomechanics (Bristol, Avon) 2001;16(4):341–7.
Wilson GJ, Wood GA, Elliott BC. The relationship between stiffness of the musculature and static flexibility: an alternative explanation for the occurrence of muscular injury. International Journal of Sports Medicine 1991;12(4):403–7.
Winter DA. Anthropometry. In: Winter DA, editor. Biomechanics and motor control of human movement. New York: Wiley and Sons Inc.; 1990. p. 59–74.