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THE RELATIONSHIP BETWEEN TRUNK MUSCLE STRENGTH AND PELVIC OSCILLATION IN ASYMPTOMATIC PHYSICALLY INACTIVE ADULTS

ORIGINAL ARTICLE

ABSTRACT

Purpose: Pelvis and trunk structure are body segments that are integrated with each other. Collaboration between pelvic mobility and trunk muscles plays a significant role in walking and energy consumption. The aim of this study is to investigate the relationship between trunk muscle strength and pelvic oscillations.

Methods: Twenty-eight healthy individuals volunteered for the study (16 women, 12 men; mean age 24.46 ± 2.97 yrs., height 172.03 ± 9.41cm, weight 67.78 ± 16.31 kg). Pelvic oscillations were measured by using a wireless tri-axial accelerometer. Trunk muscle strength was evaluated with Isokinetic Dynamometer (Cybex Humac Norm Testing & Rehabilitation System, USA). The trunk extensors and flexors were tested concentrically at 60°s. Statistically, the direction and level of the relationship were examined by using Spearman Correlation Analysis.

Results: Correlation analysis showed significant relationships between concentric strength of trunk flexion and anterior-posterior pelvic tilt ($r=-0.419$ $p<0.05$), lateral pelvic tilt ($r=-0.768$ $p<0.001$), and hip rotation ($r=-0.382$ $p<0.001$). A statistically significant relationship was not observed between concentric strength of trunk extension and anterior-posterior pelvic tilt, and hip rotation ($p>0.05$).

Conclusion: The current study reports that trunk muscle strength is associated with pelvic oscillations. In particular, the increase in the strength of the trunk flexor group muscles has been shown to limit the mobility of the pelvis. In addition, these results show that the increase in trunk muscle strength provides a stable basis for the pelvis during walking. Therefore, the authors of the current study think that a stable pelvis structure will contribute to the prevention of possible pathologies related to the lower extremity.

Key Words: Biomechanics, Gait Analysis, Muscle Strength, Trunk

ASEMPTOMATİK FİZİKSEL İNAKTİF YETİŞKİNLERDE GÖVDE KAS KUVVETİ İLE PELVİK SALINIMLAR ARASINDAKİ İLİŞKİ

ARAŞTIRMA MAKALESİ

ÖZ

Amaç: Pelvis ve gövde yapısı birbiriyle bütünleşmiş vücut bölümleridir. Pelvik mobilite ve gövde kasları arasındaki entegrasyon, yürüme ve enerji tüketiminde önemli bir rol oynar. Bu çalışmanın amacı gövde kas kuvveti ile pelvik salınımlar arasındaki ilişkiyi araştırmaktır. Yöntem: 28 sağlıklı birey çalışma için gönüllü oldu (16 kadın, 12 erkek; ortalama yaş 24,46 ± 2,97 yıl, boy 172,03 ± 9,41 cm, ağırlık 67,78 ± 16,31 kg). Pelvik salınımlar üç boyutlu kablosuz ivmeölçer kullanılarak ölçüldü. Gövde kas kuvveti İzokinetik Dinamometre (Cybex Humac Norm Testing & Rehabilitation System, USA) ile değerlendirildi. Gövde ekstansörleri ve fleksörleri 60°/sn lik açısal hızda konsantrik olarak test edildi. İstatistiksel olarak ilişkinin yönü ve düzeyi ise Spearman Korelasyon Analizi yapılarak incelendi.

Sonuçlar: Korelasyon analizi, konsantrik gövde fleksiyon kuvveti ile ön-arka pelvik eğim ($r=-0,419$ $p<0,05$), yana pelvik eğim($r=-0,768$ $p<0,001$) ve kalça rotasyonu ($r=-0,382$ $p<0,001$) arasında anlamlı ilişkiler olduğunu gösterdi. Konsantrik gövde ekstansiyon kuvveti ile ön-arka pelvik eğim ve kalça rotasyonu arasında istatistiksel olarak anlamlı bir ilişki gözlenmedi ($p>0,05$).

Tartışma: Mevcut çalışma, gövde kas kuvvetinin pelvik salınımlarla ilişkili olduğunu bildirmektedir. Özellikle gövde fleksör grup kaslarının kuvvetindeki artışın pelvis hareketliliğini sınırladığını göstermiştir. Ek olarak, bu sonuçlar gövde kas gücündeki artışın yürüyüş sırasında pelvis için stabil bir temel sağladığını göstermektedir. Bu nedenle mevcut çalışmanın yazarları, stabil bir pelvis yapısının alt ekstremite ile ilgili olası patolojilerin önlenmesine katkıda bulunacağını düşünmektedir.

Anahtar Kelimeler: Biyomekani, Yürüyüş analizi, Kas kuvveti, Gövde

INTRODUCTION

In terms of biomechanics, the human body is a multi-segmental structure that contains powerful interactions between adjacent segments. Interaction between segments that are further apart may also hold a high significance for symptom-free musculoskeletal function (1). The pelvis, an important segment, situated in the centre of the body, connects the upper body to the lower limbs (2). This is due to the central location of the pelvis; it is also highly related to gait.

Throughout the gait, the sinusoidal movements of the pelvic centre of gravity in the sagittal and frontal plane and the rotational movements in the transverse plane are considered normal, if they remain within certain limits, depending on the structural movements of the musculoskeletal system. In order to maintain the walking pattern properly and economically, control of the pelvis and hip joint must be provided by the surrounding muscles (3).

Trunk stabilization plays a key biomechanical role in minimizing the stress on the joint and maximizing the force production (4). An increase in body muscle force in this context may result in reduced energy consumption by reducing pelvic oscillations and to achieve a smooth gait pattern (5).

Interactions between the trunk and lower limbs are directly affected by pelvic joints, ligaments, and muscles. In the normal walking part, the pelvis moves by swinging forward and backward in the sagittal plane. This is at a total angle of 2-4 degrees. As a result of these movements of the pelvis, forward tilt and back tilt occur. The control of this 4-5 cm movement of the centre of gravity in the frontal plane will be difficult to control in the weakness of the pelvic and trunk muscles, and excessive tilting of the pelvis will occur, which is a pathological gait (6).

Trunk stability is defined as the ability to maintain active control of spinal and pelvic mobility during dynamic loading and static conditions (7). The structure that is effective on the pelvis and spinal mobility is the trunk flexor and extensor muscle groups. Adequate trunk muscle strength may provide a more stable pelvis and pelvic mobility. A stable pelvis structure can increase the integration between the upper extremity and lower extremity, thus promoting optimal force generation during sporting activities (8). Hence, we think that the relationship between pelvis and trunk muscle strength should be examined. In addition, in some of the studies in the literature, pelvic movements have only been evaluated in the sagittal plane and as a result, the effect of trunk flexor and extensor muscle strength on pelvic mobility has not been fully explained (9,10). The relationship between the mobility of the pelvis in all 3 planes and trunk muscle strength in individuals without any pathology has not been examined. Therefore, the aim of this study is to investigate the relationship between trunk muscle strength and pelvic oscillations in all three directions. The second purpose of the study was to compare the pelvic mobility of male and female participants.

METHODS

Participants

This cross-sectional study was conducted at Gazi University, Department of Physiotherapy and Rehabilitation in 2018. Twenty-eight physically inactive individuals volunteered for the study (16 women, 12 men; mean age 24.46 ± 2.97 yrs., height 172.03 ± 9.41cm, weight 67.78 ± 16.31 kg). Physically inactive adults were defined as individuals who did not meet the physical activity recommendations of 150 min/week of moderate-intensity exercise (11). To calculate the sample size required, the G*Power program (an α level of .05 and 80% of statistical power) and the data from the first 8 participants were used. The sample size was calculated for the primary outcome of flexor trunk muscle strength. The estimated sample size was 28 participants. Inclusion criteria were as follows; (1) 18 years or older, (2) free of back and lower-limb injury, (3) no noticeable gait abnormalities. Subjects were excluded if they had lower extremity injuries within the last 3 months or any neurological, musculoskeletal, and cardiopulmonary disorders. The individuals who were included in the study underwent analysis of pelvic movement and trunk muscular strength assessment, respectively. All participants provided written informed consent, and the study was approved by the Ethics Committee of Gazi University (Number: 77082166-302.08.01 Resaerch Code: 2018-24).

Procedure

Gait characteristics and pelvic oscillation were measured while participants walked freely along a 10-m walkway by using a wireless tri-axial accelerometer. Participants were allowed to walk with non-heeled casual shoes on firm surface. Analysis system was based on centre of mass using a wireless tri-axial accelerometer (G-Walk, BTS Bioengineering S.p.A., Italy) that was attached to the 5th lumbar vertebra and tightened with Velcro™. The accelerometer data were wirelessly transferred by a Bluetooth system and analyzed with BTS G-studio software (BTS Bioengineering S.p.A., Italy) on a computer (12). The weight of the accelerometer was 37 g, with dimensions of 70 × 40 × 18 mm. The frequency of the accelerometer was from 4 to 1000 Hz and sensor fusion was 200 Hz. Pelvic oscillation which has included all three planes (Anterior-posterior tilt, lateral tilt, and rotational) was analysed by using BTS G-studio software program. G-walk is a reliable device for evaluating gait in healthy adults. The assessment of pelvic angles had moderate test–retest reliability (ICC: 0.463-0.659) (13).

Isokinetic dynamometer was used to identify the flexor and extensor trunk muscular strength of the participants (Cybex Humac Norm Testing & Rehabilitation System, USA). Prior to the tests, isokinetic dynamometer calibration was automatically done by the device, and prior to the performances, body weight of the participants was measured with the dynamometer in passive mode to prevent the measurement results from being affected by the body weight of the participant depending on gravity and it was eliminated. In the test position, the participants were asked to step on the body apparatus and their feet were positioned on the designated area on the platform. The pelvic band was locked and placed right on the spina iliaca anterior superior. The height of the popliteal pad was adjusted by the motorized system in a way to correspond to the back of the knee joint of the participant. After positioning the knees at 15°-20° flexions, thigh and tibial pads were fixed in a way to leave the patella behind. After adjusting the height of the scapular pad at the level of spina scapula, chest pad was positioned parallel to the scapular pad on the front (14). A total of 70° range of movement was defined for a concentric test (60° flexion - 10° extension). Subjects performed concentric trunk flexion and extension for 5 repetitions at 60°/s. The intrarater and interrater reliability of trunk flexion (0.89 to 0.95) and extension (0.80 to 0.92) isokinetic strength testing had been previously established. Reciprocal concentric trunk flexion and extension peak torque measurements had good reliability with the isokinetic dynamometer in healthy subjects (15). (Figure 1 Measurement of isokinetic trunk muscle strength)

Statistical analysis

IBM Statistical Package for Social Sciences (SPSS) Statics Version 22.0 statistical software package was used in data analysis. Visual (histogram, probability graphs) and analytical methods (Kolmogorov-Smirnov/Shapiro-Wilk's test) were used to examine whether the variables showed normal distribution (16). For the variables with normal distribution, Pearson correlation analysis was used to examine the relationship between the variables in the study. For the variables not showing normal distribution, on the other hand, Spearman correlation analysis was used. Mann Whitney U Test was used for the variables not showing normal distribution in the comparison of the measurement results for the male and female individuals. The statistical error level was set at $p<0.05$.

RESULTS

32 individuals who met the inclusion criteria were included in the study. 4 individuals who had pain during the evaluation had to leave the study, a total of 28 individuals completed the study. Descriptive data and isokinetic muscle strength values of the individuals are summarized in Table 1.

A negative and moderate correlation was found between the concentric strength of trunk flexion and anterior-posterior tilt (r=-0.419). A negative and excellent correlation was observed between the concentric strength of trunk flexion and lateral tilt (r=-0.768). A low to moderate correlation was detected between the concentric strength of trunk flexion and hip rotation (r=-0.383, r=-0.382 Table 2).

Table 1. The Characteristics of The Subjects and Isokinetic Trunk Strength Values

	Female (X±SD) (n=16)	Male (X±SD) (n=12)
Body Weight (kg)	56.25±5.14	83.17±12.86
Height (cm)	165.50±4.19	180.75±6.96
Age (year)	23.56±2.94	25.67±2.67
CSOTF (PT/BW) (N-m)	117.69±52.30	211.42±73.19
CSOTE (PT/BW) (N-m)	200.50±70.54	368.25±117.18

PT/BW: Peak Torque / Body Weight. CSOTF: Concentric strength of trunk flexion. CSOTE: Concentric strength of trunk extension. N-m: Newton-meter

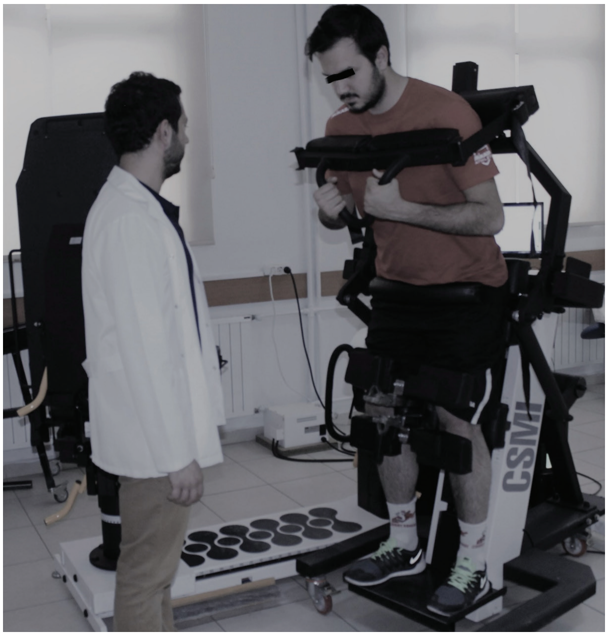

Figure 1. Measurement of Isokinetic Trunk Muscle Strength

A statistically significant relationship was not observed between the concentric strength of trunk extension and anterior-posterior tilt. A negative and moderate correlation was found between the concentric strength of trunk extension and lateral tilt (r=-0.541, r=-0.462). A statistically significant correlation was not detected between the concentric strength of trunk extension and hip rotation.

It was revealed that right (p=0.000) and left (p=0.001) lateral tilt of the females included in the study were statistically and significantly higher compared to the male individuals but there is no difference in hip rotation and anterior-posterior tilt between the male and female individuals (p>0.05 Table 3).

DISCUSSION

This study aimed to investigate the relationship between trunk muscle strength and pelvis oscillation in physically inactive individuals. Results of this study showed that concentric trunk flexor muscle strength was related at different levels in all three pelvic motion plans but extensor muscle strength was only associated with lateral pelvic tilt in the sagittal plane. In other planes, extensor trunk muscle strength was not related to pelvic motion. Also, female participants showed greater pelvic oscillation than male individuals.

The pelvis and trunk structure are body segments that are integrated with each other. Collaboration between the pelvis and trunk plays a significant role during walking and performing daily activities (17). Unfortunately, there are few studies in the literature investigating the muscular and biomechanical relationship between these structures. Steele et al. examined the relationship between lumbar kinematic variability during gait and isolated lumbar extension strength in chronic low back pain. Their study revealed that significant correlations between transverse plane pattern variability and isolated lumbar extension strength (18). The results

Table 2. The Relationship Between Isokinetic Muscle Strength and Pelvic Oscillation

	AP Tilt R		AP Tilt L		Lateral Tilt R		Lateral Tilt L		Rotation R		Rotation L	
	r	p	r	p	r	p	r	p	r	p	r	p
CSOTF	-0.327	0.090	**-0.419***	0.027	**-0.768***	<0.001	**-0.678***	<0.001	**-0.382***	0.045	**-0.383***	0.044
CSOTE	-0.010	0.959	-0.035	0.860	**-0.541**	0.003	**-0.462***	0.013	-0.094	0.634	-0.060	0.763

*p<0,05. CSOTF: Concentric strength of trunk flexion. CSOTE: Concentric strength of trunk extension. AP: Anterior Posterior. R: Right. L: Left.

Table 3. Comparison of Male and Female Pelvic Oscillations

	AP Tilt R˚	AP Tilt L˚	Lateral Tilt R˚	Lateral Tilt L˚	Rotation R˚	Rotation L˚
Female(n=16)	3.31±1.46	3.41±1.78	10.98±2.19	10.56±2.29	10.08±3.92	9.78±3.56
Male (n=12)	3.75±2.06	3.68±2.24	6.11±2.99	6.16±2.99	10.74±6.89	10.34±6.54
Asymp. Sig. (2-tailed)	0.816	0.889	**0.000***	**0.001***	0.853	0.982

*p<0,05 AP: Anterior-Posterior R: Right L: Left Asymp Sig: Asymptotic Significance ˚: Degree

of the present study were similar to Steele et al. research, in addition, our study found not only the extensor muscles group but also the flexor muscles group correlated with pelvis movement. According to these results, we think that the main function of trunk extensor and flexor muscles is to control and restrict excessive pelvic movement.

As increased pelvic oscillations will indicate a pathology, a rigid pelvis may demonstrate a trunk dysfunction. Especially low back pain patients have demonstrated more rigid sagittal and transverse planes coordination variability during walking compared with healthy (17-19) Bagheri et al. aimed to investigate the effect of core stabilization exercise program on the trunk–pelvis kinematics during gait in non-specific chronic low back pain. The results suggest that exercise programs may specifically increase transverse and frontal plane variability, indicating improved motor pattern replication through these movement planes (20). Previous researches have shown that low back pain displays a reduced trunk muscle activation pattern during gait and strengthening these muscles will restore the movements of the pelvis and spine (21). Altered pelvis biomechanics may also indicate different pathologies. Altered frontal plan pelvis kinematics have been demonstrated in patients with knee osteoarthritis (22) and lateral sway has also been related to the risk of falling in the elderly (23).

Walking is one of the most important locomotor activities of healthy individuals and the pelvis provides the basis for optimal walking properties. Gait characteristics and kinematics may differ between genders (24). Identification and knowledge of walking features will allow early intervention for pathologies that may occur. Stansfield et al. examined the characterization of gender and speed-related changes in kinematic characteristics of gait and revealed that females have 6° higher pelvic anterior tilt, and 2° higher side-up pelvic obliquity compared to males. Stansfield concluded that differences in muscular strength or muscular configuration related to anatomical differences may have been the main reason for determining outcomes between genders (25). Bruening et al. aimed to investigate the sex differences in whole-body gait kinematics. Their results showed that in the frontal plane, women walked with greater pelvic obliquity than men and females had greater transverse plane pelvis rotation. Bruening et al. suggest that men and women use different control strategies related to walking energy economy during gait (26). Smith et al. reported greater pelvic obliquity and less vertical centre of mass (CoM) displacement in women compared with men. In the frontal plan pelvic obliquity has been recognized as a mechanism to decrease the energy requirement of walking by reducing the vertical summit of the CoM's path during walking, such that the vertical displacement of the CoM is reduced (27). Wall-Scheffler et al. suggest that women are rotating their pelvis through a greater angle than men, increasing their stride length, and reducing the number of strides. With a relatively larger pelvis, females can increase their stride length through rotation alone (28). Similarly, Whitecome et al. examined the pelvic rotation effect on human stride length. Their results showed that females demonstrated greater stride length than males due to increased pelvis rotation (29). Although greater pelvic obliquity in women may be beneficial, increased pelvic obliquity may not be suitable in terms of lumbosacral adaptation (27). Like several previous studies, we also found greater lateral tilt in frontal plan in females compared with males. However, there is no difference in hip rotation and anterior-posterior tilt between male and female individuals. Sex differences may be related to differences in proportions of the body segments and musculoskeletal structure between males and females also different social and cultural factors may have affected gait biomechanics.

However, more male and female participants are needed to generalize the findings in this current study.

Walking requires metabolic energy, primarily to move the body's centre of gravity and generate muscle force (30). Higher energy cost of movement is often mentioned as a lower economy of gait. The reduced economy of gait has been related to impaired function and fatigue. Alterations in the biomechanics of gaits, such as increased pelvic obliquity, frontal plan pelvic tilt, and transverse plan rotation affect walking energy consumption (5). In 1953, Saunders and colleagues published a highly critical article and outlined that the determinants of gait as six kinematic events including pelvic rotation, pelvic obliquity, stance knee flexion, foot and ankle mechanisms, and tibiofemoral angle. These determinants help to reducing vertical displacement of the body's centre of mass. Saunders et al. suggested that reducing the vertical displacement of the body's CoM would result in a more energy-efficient gait (31). Although this concept has been widely accepted, particularly in clinical biomechanics, it has not been meticulously tested until recently. Contrary to the view of Saunders et al. several research hypothesized that metabolic cost would not decrease when humans walk with reduced vertical CoM displacement (32-34). Ortega et al. examined the metabolic cost and mechanical energy exchange, for humans walking with small vertical movements of the centre of mass compared with walking with normal centre of mass movements. Results of this study showed that in flat-trajectory walking, subjects reduced centre of mass vertical displacement by an average of 69% but consumed approximately twice as much metabolic energy (33). The vertical movements of the body's CoM allow the exchange between potential and kinetic energy during each stride and thereby reduce mechanical work required to move body's CoM (35). It could be speculated that an intermediate amount of vertical displacement is optimal for the passive exchange of energy and minimizes energy expenditure during walking (36). Energy consumption was not primarily evaluated in the current study. However, in light of previous studies, it is not possible to decide the walking economy by examining only the pelvic movement of individuals. All other body segments should be analyzed in the evaluation of the gait economy.

The present study has some limitations, the main limitation of this study is that young and physically inactive adults will be included, thereby, the generalizability is limited. If individuals or athletes with different activity levels were included, we might have seen different results. Second, we did not evaluate intersegment trunk–pelvis kinematic pattern during gait. Some researchers suggest that upper and lower segments may acts differently during trunk motions. Another limitation of our study is that energy consumption was not evaluated in addition to pelvic mobility during walking. Therefore, it is difficult to interpret the change in energy consumption due to pelvic mobility.

Trunk muscle strength was found to be associated with pelvic oscillations, and these pelvic oscillations constitute the mobility of the pelvis. Our findings suggest that increase in trunk muscle strength provides a stable basis for the pelvis during walking. Therefore, authors of the current study think that stable pelvis structure will contribute to the prevention of possible pathologies related to the lower extremity. Optimal gait pattern involves multiple determinants. Synchronization of all related body segments, proper biomechanics and muscular coordination are required for the appropriate gait cycle. Although trunk muscle strength and pelvic mobility are important determinants of gait, they are insufficient to evaluate the whole gait cycle. Future research should simultaneously examine the relationship between pelvic mobility and muscular activation, kinematic analysis, and energy expenditure during walking.

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KAYNAKLAR

1. Bagherian S, Ghasempoor K, Rahnama N, Wikstrom, EA. The effect of core stability training on functional movement patterns in college athletes. J Sport Rehabil. 2019;28(5):444-449.
2. Celenay ST, Ozkan T, Unluer NO. Short-term effects of trunk kinesio taping on trunk muscle endurance and postural stability ın healthy young adults: a randomized controlled trial. Turk J Physiother Rehabil. 2019;30(2):89-96.
3. Kim TH, Lee CW, Kim SG, An, BW. The effect of a pelvis-concentrated exercise program on male college students' body alignment and foot base pressure. J Phys. Ther. Sci. 2015;27(4):1165-7.
4. Tsai YJ, Chia CC, Lee PY, Lin LC, Kuo YL. Landing kinematics, sports performance, and isokinetic strength in adolescent male volleyball athletes: influence of core training. J Sport Rehabil. 2020;29(1):65-72.
5. Katzel LI, Ivey FM, Sorkin JD, Macko RF, Smith B, Shulman, LM. Impaired economy of gait and decreased six-minute walk distance in Parkinson's disease. J Parkinsons Dis. 2012;2012.
6. Hammer N, Scholze M, Kibsgård T, Klima S, Schleifenbaum S, Seidel T, et al. Physiological in vitro sacroiliac joint motion: a study on three-dimensional posterior pelvic ring kinematics. J Anat. 2019;234(3):346-58.
7. Jeong, J, Choi DH, Shin CS. Core strength training can alter neuromuscular and biomechanical risk factors for anterior cruciate ligament injury. Am J Sports Med. 2021;49(1): 183-192.
8. Zazulak B, Cholewicki J, Reeves PN. Neuromuscular control of trunk stability: clinical implications for sports injury prevention. J Am Acad Orthop Surg. 2008;16(8):497-505.
9. Arampatzis A, Frank J, Laube G, Mersmann F. Trunk muscle strength and lumbo-pelvic kinematics in adolescent athletes: Effects of age and sex. Scand J Med Sci Sports. 2019;29(11): 1691-1698.
10. Kuszewski MT, Gnat R, Gogola A. The impact of core muscles training on the range of anterior pelvic tilt in subjects with increased stiffness of the hamstrings. Hum Mov Sci. 2018;57:32-9.
11. American College of Sports Medicine. ACSM's exercise testing and prescription. Lippincott williams & wilkins. Philadelphia; 2017.
12. Park G, Woo Y. Comparison between a center of mass and a foot pressure sensor system for measuring gait parameters in healthy adults. J Phys Ther Sci. 2015;27(10):3199-202.
13. Yazici G, Yazici MV, Çobanoğlu G, Kupeli, B, Ozkul C, Oskay D, et al. The reliability of a wearable movement analysis system (g-walk) on gait and jump assessment in healthy adults. J Exerc Ther Rehabil. 2020;7(2):159-67.
14. Kim CG, Jeoung BJ. Assessment of isokinetic muscle function in Korea male volleyball athletes. J Exerc Rehabil. 2016;12(5):429.
15. García-Vaquero MP, Barbado D, Juan-Recio C, López-Valenciano A, Vera-Garcia FJ. Isokinetic trunk flexion–extension protocol to assess trunk muscle strength and endurance: reliability, learning effect, and sex differences. J Sport Health Sci. 2020;9(6):692-701.
16. Finner H, Gontscharuk V. Two-sample Kolmogorov–Smirnov-type tests revisited: old and new tests in terms of local levels. Ann Stat. 2018;46(6A):3014-37.
17. Seay JF, Van Emmerik RE, Hamill J. Low back pain status affects pelvis-trunk coordination and variability during walking and running. Clin Biomech. 2011;26(6):572-8.
18. Steele J, Bruce-Low S, Smith D, Jessop D, Osborne N. Lumbar kinematic variability during gait in chronic low back pain and associations with pain, disability and isolated lumbar extension strength. Clin Biomech. 2014;29(10):1131-8.
19. Ebrahimi S, Kamali F, Razeghi M, Haghpanah SA. Comparison of the trunk-pelvis and lower extremities sagittal plane inter-segmental coordination and variability during walking in persons with and without chronic low back pain. Hum Mov Sci. 2017;52:55-66.
20. Bagheri R, Parhampour B, Pourahmadi M, Fazeli SH, Takamjani IE, Akbari M, et al. The effect of core stabilization exercises on trunk–pelvis three-dimensional kinematics during gait in non-specific chronic low back pain. Spine J. 2019;44(13):927-36.
21. Lamoth CJ, Meijer OG, Daffertshofer A, Wuisman PI, Beek PJ. Effects of chronic low back pain on trunk coordination and back muscle activity during walking: changes in motor control. Eur Spine J. 2006;15(1):23-40.
22. Hunt MA, Wrigley TV, Hinman RS, Bennell KL. Individuals with severe knee osteoarthritis (OA) exhibit altered proximal walking mechanics compared with individuals with less severe OA and those without knee pain. Arthritis Care Res. 2010;62(10):1426-32.
23. Chiba H, Ebihara S, Tomita N, Sasaki H, Butler JP. Differential gait kinematics between fallers and non-fallers in community-dwelling elderly people. Geriatr Gerontol Int. 2005;5(2):127-34.
24. Kobayashi Y, Hobara H, Heldoorn TA, Kouchi M, Mochimaru M. Age-independent and age-dependent sex differences in gait pattern determined by principal component analysis. Gait Posture. 2016;46:11-7.
25. Stansfield B, Hawkins K, Adams S, Bhatt H. A mixed linear modelling characterisation of gender and speed related changes in spatiotemporal and kinematic characteristics of gait across a wide speed range in healthy adults. Med Eng Phys. 2018;60:94-102.
26. Bruening DA, Frimenko RE, Goodyear CD, Bowden DR, Fullenkamp AM. Sex differences in whole body gait kinematics at preferred speeds. Gait Posture. 2015;41(2):540-5.
27. Smith LK, Lelas JL, Kerrigan DC. Gender differences in pelvic motions and center of mass displacement during walking: stereotypes quantified. J Wom Health Gend Base Med. 2002;11(5):453-8.
28. Wall-Scheffler CM, Myers MJ. The biomechanical and energetic advantages of a mediolaterally wide pelvis in women. Anat Rec. 2017;300(4):764-75.
29. Whitcome KK, Miller EE, Burns JL. Pelvic rotation effect on human stride length: Releasing the constraint of obstetric selection. Anat Rec. 2017;300(4):752-63.
30. IJmker T, Lamoth CJ, Houdijk H, van der Woude LH, Beek PJ. Postural threat during walking: effects on energy cost and accompanying gait changes. J Neuroeng Rehabil. 2014;11(1):71.
31. Inman VT, Eberhart HD. The major determinants in normal and pathological gait. J Bone Joint Surg Am. 1953;35(3):543-58.
32. Gordon KE, Ferris DP, Kuo AD. Metabolic and mechanical energy costs of reducing vertical center of mass movement during gait. Arch Phys Med Rehabil. 2009;90(1):136-44.
33. Ortega JD, Farley CT. Minimizing center of mass vertical movement increases metabolic cost in walking. J Appl Physiol. 2005;99(6):2099-107.
34. Wurdeman S, Raffalt P, Stergiou N. Reduced vertical displacement of the center of mass is not accompanied by reduced oxygen uptake during walking. Sci Rep. 2017;7(1):1-13.
35. Alexander RM. Simple models of human movement. Appl Mech Rev. 1995;48(8):461-470.
36. Kuo AD. The six determinants of gait and the inverted pendulum analogy: A dynamic walking perspective. Hum Mov Sci. 2007;26(4):617-56.