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The gastrocnemius muscle stiffness and human balance stability

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1. Introduction

The ability to maintain stability during quiet standing is very important in clinical practice. With the increase in aging of population and with increased life expectancy of the elderly people, the importance of maintaining mobility, and consequently functional independence, is becoming more and more important [1]. Stevens [2] had reported that the direct medical cost incurred with falling of patients or aged people was up to 19 billion dollars in 2000 in the USA. The changes of the balance control system of elderly [3] and main pathologies, has forced researchers and clinicians to understand more about how the system works and how to quantify its status at any point in time. The following factors such as Parkinson's disease [4], diabetes mellitus [5], and many more can influence the human standing posture directly or indirectly. Therefore, research on the balance stability became an important branch of neuroscience, and its functioning units include muscles, skeletons, and peripheral sensors to the central neural system [6].

Biomechanical stability of quiet standing can be defined as the joint ability to maintain equilibrium in response to an external perturbation or load [7, 8]. Visual, vestibular, proprioceptive, tactile, and muscular factors, all contribute to the biomechanical stability of a joint, however the stiffness properties of the surrounding muscle is reported to be the most critical parameters [9-11]. The concept of a simple muscle stiffness control of balance during quiet standing was introduced by Winter et al. [10].

The most common model used to characterise the postural control during quiet standing is the inverted pendulum. According this model the postural control is defined by the relation between the centre of pressure (COP) and the centre of mass (COM) [10]. The COP is the integrated control variable whereas the COM is the controlled variable. The COP is defined as the point of application of the ground reaction forces under the feet measured by one or two force platforms. The COM is an imaginary point at which the total body mass can be assumed to be concentrated. The position of the COM is hypothesised to be subject to body postural control [12]. Sway of COP is typically measured by means of a force platform.

Most research analyzing influence of leg muscles stiffness on postural stability is found on inverted pendulum model. According to the inverted pendulum model the frequency and amplitude of oscillations depend on the spring stiffness and the inertia [10]. Scientific research found on different models enables to assess the leg muscle stiffness during quiet standing. But we haven‘t found the experimental data about changes of balance stability parameters standing with relaxed and actively contracted muscles.

According to inverted pendulum model the higher stiffness of leg muscles should increase the frequency of COP sway and decrease the amplitude, thus increase balance stability. The aim of this study was to assess the dependence of postural stability on gastrocnemius muscle stiffness parameters.

2. Subjects and methods

44 healthy students (18 males and 26 females) of Lithuanian academy of physical education aged 22-26 years voluntary participated in the trial. Their height – 174.9 ± 9.4 cm (from 162 to 187 cm), weight – 68.7 ± 13.8 kg (from 50 to 81 kg).

2. 1. Myotonometry

There are many muscles participating in postural control, however for evaluation we chose gastrocnemius muscle (*m. gastrocnemius caput mediale*). The gastrocnemius muscle along with soleus muscle forms calf muscle and it is more superficial than soleus. Therefore it is possible to apply noninvasive research methods. The gastrocnemius muscle it is known as the most important in plantar flexion of the foot, also it takes part in balance ankle strategy during quite standing.

The volunteers were instructed to perform plantar flexion with maximal efforts. Muscle tone was measured during full plantar flexion of the foot and full knee extension. The stiffness of medial head of the muscle in the relaxed and maximally contracted state was measured while lying prone during myotonometry with MYOTON-3 device designed in University of Tartu (Estonia) [13]. Principles of the myotonometry lie in using of acceleration probe to record the reaction of the peripheral skeletal muscle or its part to the mechanical impact and the following analysis of the resulting signal with the aid of the personal computer. Myoton exerts a local impact on the biological tissue by means of a brief impulse which is shortly followed by a quick release. The tissue responded to the mechanical impact with damped oscillations. The oscillations were recorded by the acceleration transducer at the testing end of the device. The oscillation frequency f, the logarithmic decrement of damping δ, and stiffness K were estimated.

2. 2. Static posturography

The equilibrium testing was performed using static posturography method [14]. The posturogram signals were registered by means of the force platform MA-1 and analyzed using the customer designed software. The sway of COP (posturogram) was registered in sagittal and transverse directions. Signals were sampled using 100 Hz sampling frequency and 12 bit resolution using PC Data acquisition card CYDAS-1400 (Cyber Research, USA). The posturogram (signal reflecting the COP sway) was registered when the eyes were open. Volunteers were asked to stand quietly with maximum contracted calf mucles and look at the marked point in front of them. The legs were closed together with arms at the sides.

The maximal length of COP dislocation in transverse (Δx) and sagittal direction (Δy), the mean velocity of COP oscillations ($\bar{v}$) were estimated.

COP position reflecting signal has a stochastic background, but actions of known mechanisms of autonomic balance control are reflected in different frequency domains. Methods of evaluation of the COP signal in time-frequency domain could show extended possibilities revealing actions of parts of the whole system. Multiresolution analysis based on discrete wavelet transform was used for COP signal decomposition [15]. The signal was decomposed into 6 components (Table 1).

Table 1

COP signal decomposition into 6 components (scales) covering following frequency bands

Scale number	Frequency, Hz
1	2.5-5.0
2	1.25-2.5
3	0.625-1.25
4	0.312-0.625
5	0.156-0.312
6	0.078-0.156

The COP position reflecting signal and the components of it we qualified as power signal (the integral of which in the range from -∞ till ∞ is infinite, according [16]. Therefore average power of each component was estimated according following formula

$$P_S = \frac{1}{N}\sum_{i=0}^{N-1}\left|s_i - M_S\right|^2 \quad (1)$$

where s_i is the ordinary sample of scale S and M_S – is the average of the same scale S.

2. 3. Statistics

The effect of muscle stiffness on the posturometric parameters was assessed with a bivariate correlation, nonlinear regression and with repeated-measures ANOVA on the task conditions. The linear relationship in association of the mean velocity of the COP movement and muscle stiffness, of the wavelets energies at different resolution scales and muscle stiffness was assessed with Pearson correlation coefficient, whereas the nonlinear relationship in association of the wavelets energies at different resolution scales and mean velocity of the COP movement was assessed with nonlinear regression and R-square – coefficient of determination. The bivariate correlation and ANOVA was evaluated as significant when there was $\alpha < 5\%$ chance of making a type I error ($p < 0.05$). All statistical analysis was performed by means of statistical package SPSS 17.0.

3. Results

A striking difference between the two posturograms of sway of COP in the transverse and sagittal direction during quiet stance with relaxed and actively contracted leg muscles lies in their smoothness (Fig.1). The COP shift trace during standing with relaxed muscles appears much smoother than during standing with actively contracted muscles although the character of it is not homogeneous.

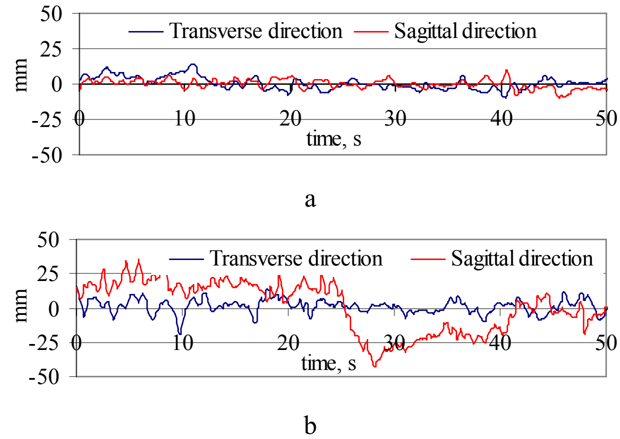


Fig. 1 The sway of COP of the same subject during quite standing with relaxed and actively contracted leg muscles in transverse and sagittal directions. a – legs muscles relaxed, b – legs muscles actively contracted

The posturometric and myometric data show that active contraction of the leg muscles significantly increased maximal length of COP dislocation in transverse and sagittal directions, the mean velocity of the COP sway, the oscillation frequency and stiffness of calf muscles (*m. gastrocnemius*) (Table 2).

Table 2

Stabilometric and myometric data standing with relaxed and actively contracted leg muscles

		Muscles relaxed, Mean± SD	Muscles contracted, Mean± SD
Stabilometric data	Δx, mm	22.14±6.81	26.00±8.41**
	Δy, mm	25.53±10.49	34.86±15.81**
	$\bar{v}$, mm/s	11.49±2.55	18.88±5.66**
Myometric data	f, Hz	15.79±3.04	19.68±5.23**
	δ	1.02±0.35	1.17±1.58
	K, N/m	333.29±73.17	471.24±111.01**

** – difference is significant at the 0.01 level

The contraction of muscle significantly increase its own oscillation frequency from 15.79±3.04 Hz to 19.68 ± 5.23 Hz ($p < 0.01$) and stiffness from 333.29 ± 73.17 N/m to 471.24 ± 111.01 N/m ($p < 0.01$) (Table 2). Thus, active contraction of the leg muscles increases COP sway frequency and magnitude.

Discrete wavelet transform was used for COP signal decomposition into 6 components with the aim to highlight differences of COP sway in different frequency ranges. We observed significant increase of the power of component of higher frequency (0.3 – 5.0 Hz) with active contraction of the leg muscles (Fig. 2). Therefore, COP oscillation frequency tends to be higher when subject actively contracts leg muscles.

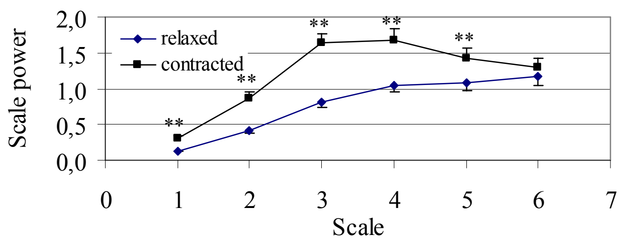
Correlation coefficient was calculated between main posturometric and myometric data to estimate relation between gastrocnemius stiffness and balance stability. Nonlinear correlation was found between power of scale and COP sway mean velocity. Linear correlation was found between other myometric and posturometric parameters (Table 3). Strong correlation ($p < 0.01$) was found between mean velocity of the COP movement and gastrocnemius stiffness.

Table 3

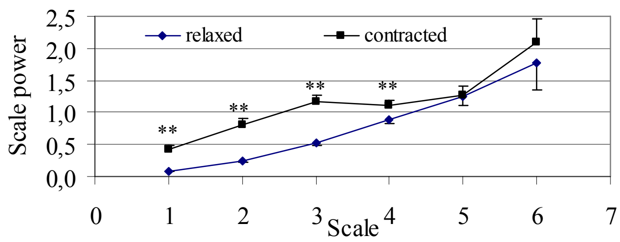
Pearson correlation coefficients between stabilometric and myometric data

	Δx	Δy	$\bar{v}$	f	δ
Δx	1				
Δy	0.326**	1			
$\bar{v}$	0.485**	0.525**	1		
f	0.263*	0.196	0.605**	1	
δ	0.039	-0.045	0.006	-0.031	1
K	0.286**	0.341**	0.651**	0.787**	-0.195

* – correlation is significant at the 0.05 level; ** – correlation is significant at the 0.01 level



a



b

Fig. 2 The power of scales of wavelet transform while standing with relaxed and actively contracted leg muscles. a – transverse direction, b – sagittal direction. Presented mean ± standard error. ** – $p < 0.01$

The plot of average power of the scale 1 (2.5 – 5 Hz) versus mean velocity of COP sway in transverse direction is presented in Fig. 3. It is close to quadratic dependency, what is highly expected while energy of the signal produced by harmonic oscillator is proportional to the average velocity in power of 2: $E = \frac{m\pi^2}{8}\bar{v}^2$. The principle well fitted in higher frequency range (> 2.5 Hz), was not so good for the average power in the lower frequencies (< 2.5 Hz). Determination coefficients were estimated using nonlinear regression model $y = A + Bx^C$ using least squares fit.

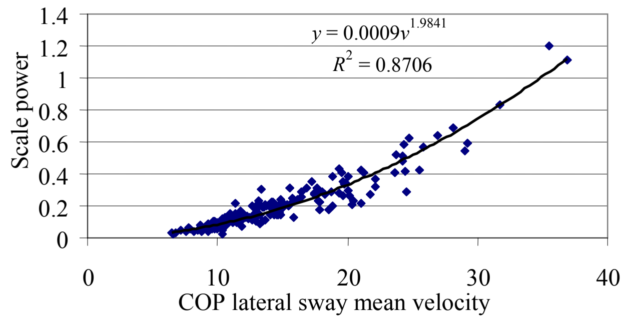


Fig. 3 The dependence between power of scale 1 (2.5 – 5.0 Hz) and sway velocity of COP in transverse direction

Determination coefficients (R^2) between average power in different scales and mean velocity of the COP movement are presented in Fig. 4. The values of R^2 for average power and $\bar{v}$ are significantly higher in higher frequency range (scales 1-3). A rather tight correlation is observed between average power of the scale and muscle stiffness ($r \approx 0.6$) (Fig. 5). It shows that straining of the muscles increases COP sway in higher frequency range.

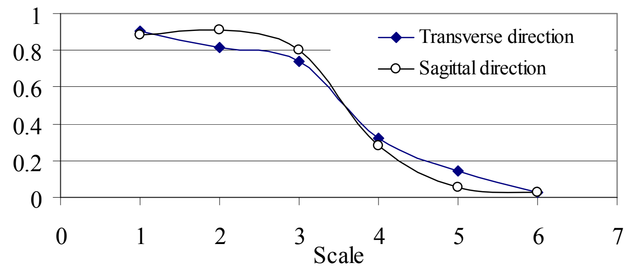


Fig. 4 The coefficient of determination (R^2) between scale power and the mean velocity of the centre of pressure movement

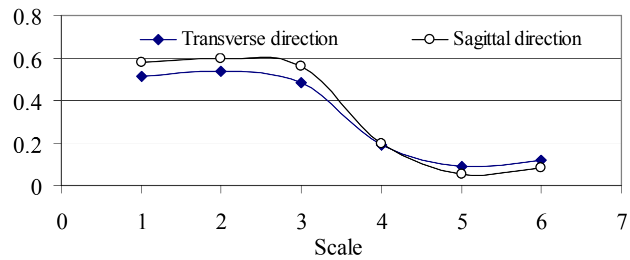


Fig. 5 The correlation coefficient between scale power and muscle stiffness (K)

4. Discussion

The aim of the research was to assess COP sway dependence on active contraction of leg muscles. Inverted pendulum model suggests an increase in frequency of COP sway and at the same time a decrease in amplitude while stiffness of the muscles is increased. In fact we observed increased average power in high frequency components of COP signal, however magnitude of COP sway contrarily to the model was increasing. This suggests that inverted pendulum model explains only higher frequency range of the COP sway signal.

The muscle stiffness is different from muscle extensibility or flexibility, which refers to the available range of motion at a joint and does not take into consideration the amount of resistive force during muscle lengthening. The stiffness of inactive muscles (passive muscle stiffness) is likely influenced by muscle extensibility/flexibility. Research has shown, however, that stiffness contributions from the passive soft-tissue structures alone are insufficient to stabilize upright standing [9]. As such, muscle extensibility/flexibility is not likely to play a major role in determining the biomechanical stability of a joint.

The stiffness contribution from actively contracting muscles (active muscle stiffness) surrounding the joint is the most important for maintaining biomechanical stability of the joint. The functional and physiologic relevance of active muscle stiffness is significant because it limits excessive joint motion and translation. Insufficient active muscle stiffness at the time of external perturbation might allow excessive muscle lengthening, which results in uncontrolled arthrokinematic motion and can increase ligament loading and injury risk [8].

Postural control requires coordinated muscle action [17]. As the muscles act about the joints in balancing the body, especially the roles of the ankle, knee and hip joints are essential. According to the passive stiffness control model, ankle stiffness, as a result of the CNS being limited to the selection of appropriate muscle tonus, stabilizes the unstable mechanical system in quiet stance [10]. However, other researchers have pointed out the active mechanism of postural stabilization in balanced stance [17, 18], where the muscle and foot skin receptors play an essential role [18].

Three movement strategies for the control of postural stability have been identified in healthy adults. In the ankle strategy, the body can be regarded as a stiff pendulum, and balance adjustments are mainly made in the ankle joint, with the person swaying like an inverted pendulum [19]. In the hip strategy, the resulting motion is primarily focused about the hip joints [20]. The third way to achieve a balanced standing position in more difficult conditions is to take steps [20]. It has been proved that subjects can synthesise different postural movements by combining strategies of different magnitudes and temporal relations that are influenced by the subject's recent experience [20].

Although the calf musculature is activated first to provide postural control during body movements [19], the co-activation of certain "prime postural muscles", such as the neck muscles, the hamstring musculature, the soleus and supraspinalis muscles, occurs in this order [17, 19]. Apart from these, however, several muscles participate in producing both reflective movements with different latency times and voluntary movements to balance the body position [19]. Whenever the muscles are stretched, the proprioceptive receptors within the muscle and tendon are sending the signal about the change in muscle length to the central mechanism of the postural control system [21].

Inverted pendulum model suggests increase in frequency of COP sway and at the same time decrease in amplitude while stiffness of the muscles is increased. In fact we observed increased average power in high frequency components of COP signal; however magnitude of COP sway contrarily to the model was increasing. This suggests that inverted pendulum model explains only higher frequency range of the COP sway signal. The whole frequency range signal reflects the response of the whole system, where CNS actions should be taken into account.

5. Conclusions

The active leg muscle contraction increases muscle stiffness and decreases postural stability during quiet stance.

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DVILYPIO BLAUZDOS RAUMENS STANDUMAS IR ŽMOGAUS PUSIAUSVYROS STABILUMAS

R e z i u m ė

Šio darbo tikslas – ištirti dvilypių blauzdos raumenų standumo ir žmogaus pusiausvyros stabilumo tarpusavio priklausomybę. Matavome įtempto ir atpalaiduoto dvilypio blauzdos raumens vidinės galvos standumą. Posturogramą registravome ramiai stovint, atpalaidavus ir įtempus kojų raumenis. Kojų raumenų įtempimas gerokai padidino slėgio centro (SC) didžiausiąjį poslinkį skersine ir strėline kryptimis, taip pat SC vidutinį judėjimo greitį ir raumens standumą. Posturogramos signalo dekompozicijai taikėme diskretinę Daubechie šeimos 4 eilės vilnelių transformaciją. Įtempus kojų raumenis, SC svyravimų dažnių spektras pasislinko aukštesniųjų dažnių link. Nustatėme gana gerą koreliacinį ryšį tarp raumens standumo ir SC vidutinio judėjimo greičio. Didelį sando galios ir SC vidutinio judėjimo greičio tarpusavio determinacijos koeficientą nustatėme aukštesniųjų dažnių srityje. Šioje srityje geras koreliacinis ryšys yra tarp sando galios ir raumens standumo. Apibendrinant tyrimų duomenis, galima teigti, kad kojų raumenų įtempimas sumažina žmogaus pusiausvyros stabilumą ramiai stovint; įtempus kojų raumenis SC svyravimų spektre didėja aukštųjų dažnių įtaka.

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THE GASTROCNEMIUS MUSCLE STIFFNESS AND HUMAN BALANCE STABILITY

S u m m a r y

The aim of this study was to assess the dependence of postural stability on stiffness of the leg muscles. The stiffness of medial head of the relaxed and actively contracted gastrocnemius muscle was measured. The posturogram was registered during quite standing with relaxed and actively contracted leg muscles. The contraction of the leg muscles significantly increased maximal shift of center of pressure (COP) in transverse and sagittal direction, the mean velocity of COP, and muscle stiffness. Multiresolution analysis based on discrete wavelet transform using 4th order Daubechie family wavelets was used for COP signal decomposition. The power of component of higher frequency significantly increased with active maximum contraction of the leg muscles. Therefore, COP oscillation frequency tends to be higher when subject actively contracts the leg muscles. High correlation observed between muscle stiffness and mean velocity. High coefficient of determination was established between the power of component and mean velocity in high frequency scale. Thus it can be stated, that active leg muscle contraction increases muscle stiffness and decreases postural stability during quiet stance; also it increases COP oscillations in high frequency scales.

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УПРУГОСТЬ ИКРОНОЖНОЙ МЫШЦЫ И СТАБИЛЬНОСТЬ РАВНОВЕСИЯ ЧЕЛОВЕКА

Р е з ю м е

Цель данной работы – оценить влияние упругости мышц ног на стабильность равновесия человека. Измеряли упругость натянутой и расслабленной икроножной мышцы. Постурограмму регистрировали при расслабленной стойке и натянутых мышц ног. Натяжение мышцах ног достоверно увеличивало максимальное перемещение центра давления (ЦД) в поперечном и сагитальном направлениях, среднюю скорость движения ЦД и упругость мышцы. Для декомпозиции постурограммы применяли метод непрерывного вейвлет-преобразования. При натяженных мышцах ног спектр частоты колебаний ЦД перемещался в область более высоких частот. Наблюдали достаточно хорошую корреляционную связь между упругостью мышцы и средней скоростью движения ЦД. Хорошую связь наблюдали между мощностью компоненты и средней скоростью движения ЦД в области более высоких частот, а также между мощностью и упругостью мышцы. Вывод: натяжение мышц ног уменьшает стабильность равновесия человека, а в спектре колебаний ЦД увеличивается вклад более высоких частот.

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