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Muscles limiting the sit-to-stand movement An experimental simulation of muscle weakness

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ABSTRACT

Adapted strategies in rising from a chair occur with muscle weakness. To assess whether muscle weakness caused the strategy change, an experimental simulation was performed that allowed to investigate separately effects of reduced muscle capacity and of strategy change on movement dynamics. It was hypothesized that a sit-to-stand (STS) strategy change spares muscles that become overloaded when muscle weakness develops. Ten healthy females participated; seven of them completed all tests. Muscle weakness causes an increased load-over-capacity ratio. In the present study, this ratio was increased by providing participants with a waist-coat containing 45% of their body mass. Participants performed sit-to-stand manoeuvres with and without added mass; moreover they were instructed to perform two different strategies, the momentum-transfer-strategy and the stabilization-strategy. During these STS-tasks sagittal 2D-video analysis were made and ground reaction forces (GRF) were measured. Joint moments and powers for ankle, knee and hip joint were calculated. The preferred strategy under the normal condition was the momentum-transfer strategy. Increasing the load without adapting the strategy resulted in significantly higher (13%) knee-joint extension moments. Allowing a strategy shift in the loaded condition spared the knee-joint extensors (−6%) and transferred effort to hip-joint extensors (57%) and plantar flexor (67%) muscles. These results suggest that the capacity of knee-joint extensors limits the STS-performance when muscle weakness occurs.

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1. Introduction

The sit-to-stand (STS) movement is a prerequisite for participation in many activities of daily living. In terms of balance it is difficult; rising from a seat involves an unstable movement from a static, stable position to a quasi-static position [1]. People with muscle weakness, like many elderly and chronically diseased people, encounter frequently problems with this movement; it is often the cause of falling.

Healthy adults perform the STS-movement by a small flexion of the trunk; subsequently they start rising from the chair. The movement ends in an erect standing position and the achievement of stability. This has been referred to as the *momentum-transfer-strategy* [2]. In people with muscle weakness rising from a chair is characterized by increased flexion of the trunk prior to rising from the seat [3–8]. This strategy has been referred to as the *stabilization-strategy* [2].

It has been suggested that muscle weakness is a major determinant of this strategy shift. Hughes et al. [9] investigated the role of strength in rising from a chair in elderly. They reported knee-joint extensors to be more than 50% weaker in elderly than in young adults; consequently, rising from a low chair required 97% of the available, isometric knee-joint extensor strength in elderly. Another study [10] showed that for STS healthy subjects activated knee-joint extensors up to 90%. Accordingly, an association between knee-joint extensor strength and the stand-up performance in elderly women was found [11]. Additionally it has been suggested that the stabilization-strategy is preferred when execution of the momentum-transfer-strategy is out of reach due to weakness of a specific muscle group [9,11]. The stabilization-strategy might thus be a way to spare the weakest muscle group. However, the cross-sectional nature of these studies does not allow assessing whether muscle weakness causes a strategy shift or whether strategy shift and muscle weakness have another, common cause.

It is the aim of this study to separately manipulate relative muscle capacity [12] and strategy selection. In this way the hypothesis will be tested that STS-strategy change occurs to unload a specific muscle group that becomes overloaded in the momentum-transfer-strategy.

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2. Methods

2.1. Subjects

Ten young women participated in this study and gave their informed consent (age: 18–28 years; body mass: 61.6 (6.7) kg; body mass index (BMI): 21.7 (1.5) kg/m²). None of the subjects experienced any musculoskeletal impairment. All subjects participated in sport activities at least once a week.

2.2. Experimental procedures

Subjects performed the STS under two load/capacity ratios and in two different strategies. To simulate muscle weakness, the load/capacity ratio was manipulated [12] by adding 45% of the subjects' body mass to a weight-vest. The weight-vest ensured a fair distribution of the mass. Subjects performed the STS with and without the added mass in a self-selected strategy. In addition, subjects were asked to perform the opposite strategies. Within the no-load condition the momentum-transfer-strategy represented the 'natural' strategy ('MomT-natural'). The stabilization-strategy was under the no-load the 'forced' execution ('Stab-forced'). Under the added load condition the stabilization-strategy was the preferred approach ('Stab-natural-L') and the momentum-transfer-strategy was executed as the forced strategy ('MomT-forced-L'). Each condition was performed twice.

The starting position was standardized. The subject sat on a height-adjustable stool, without a back support or arm rests. The trunk was in a vertical position, arms were crossed in front of the chest and the feet were symmetrically placed on the force platform with 5 cm distance between them. The knees were flexed 90°. Subjects were allowed to practice the STS movement before the actual data collection started. This experimental set-up both feet on the same force platform assumed the STS-movement to be conducted symmetrically.

2.3. Instrumentation

Reflective markers were attached to the subjects' skin at the head of the fifth metatarsal joint, the lateral malleolus, the tuber calcanei, the collateral lateral ligament at the knee joint, the greater trochanter and the lateral and prominent border of the acromion. A digital video camera (50 Hz; MX5, Adimec, The Netherlands) with a 12.5 mm lens (Ernitec) was used to collect images.

A force platform (Kistler type 9281A) was used to determine the magnitude, direction and point of application of the ground reaction force (GRF).

2.4. Data analysis

2.4.1. Temporal characteristics

Starting of the STS-movement was defined as the first movement of the shoulder marker. The movement was completed when the hip joint angle was maximal. The first vertical displacement of the hip marker, determined the instant rising from the seat started. Based on these definitions the duration of the total movement and of the flexion-momentum phase were determined (Schenkman et al. [13]). Moreover, the relative contribution of the flexion-momentum phase to the total movement was calculated.

2.4.2. Strategy

The hip-joint angle was defined as the angle enclosed at the anterior side of the body by the line through markers on the knee joint and the hip joint and the line through markers on the hip joint and the shoulder. The minimal hip-joint angle was used to confirm the strategy that was used.

2.4.3. Accelerations of the centre of mass

Vertical (a_z) and sagittal (a_y) accelerations of the body centre of mass (CoM) were calculated:

$$a_z = \left(\frac{F_z}{m} \right) - g \quad (1)$$

$$a_y = \left(\frac{F_y}{m} \right) \quad (2)$$

where F_z , F_y = vertical and sagittal ground reaction force, a_z , a_y = vertical and sagittal acceleration, g = gravitational acceleration, m = subject's body mass (plus added mass).

These accelerations provide information about postural balance; a larger range of accelerations, especially in the anterior-posterior direction, indicates less stability.

2.4.4. Dynamic characteristics: Net joint moment, impulse, power and work

Inverse dynamics was applied to calculate net moments at the hip, knee and ankle joints [14]. Based on segment lengths and a regression model [14], the masses, the moments of inertia and the locations of the centres of masses of the segments were estimated. Segment lengths were derived from distances between the relevant markers. The forces on the stool were not measured. Therefore, net joint moments were calculated from the instant rising from the seat started till the end of the movement. Maximal hip and knee-joint extension moments and maximal ankle plantar flexion moment were determined. Also the impulses resulting from the respective net joint moments were calculated.

Instantaneous powers at the hip, knee and ankle joints were obtained by multiplying net joint moments by instantaneous joint angular velocities. Multiplication of power by the time required, resulted in net work at each joint.

To separate the effect of increasing body mass from the effect of changing the load/capacity ratio, all kinetic data were normalized for the individual's body mass or in the loaded conditions for the body mass and the added mass.

2.5. Statistical analyses

To determine the effects of load/capacity ratio, strategy and the interaction of these factors a General Linear Model for repeated measurements was applied (SPSS 15.0). In this model load/capacity ratio and strategy were defined as within-subject factors. $P = 0.05$ was chosen as the level of significance. Normal distribution of data was checked a priori using Shapiro-Wilk test. Data appeared to be distributed normally.

3. Results

Nine subjects completed all measurements. Due to limited ankle-joint mobility, one subject could not perform normal STS-movements. Furthermore, in one subject the data for one condition were not available, and the data in two conditions were missing in another subject. Statistical analyses were performed on the complete data sets of seven participants.

3.1. Temporal characteristics

Under the MomT-natural condition total movement time was significantly shorter than in the other conditions (Table 1). The absolute flexion-momentum phase did not differ; however its relative contribution to the entire movement was significantly shorter in the loaded conditions (Table 1).

Table 1
Duration of movement parts and acceleration of COM.

	Conditions				P-values		
	MomT-natural	Stab-forced	MomT-forced-L	Stab-natural-L	Load	Strategy	Load* Strategy
Total movement time (s)	1.7 (2.0)	2.2 (0.3)	2.2 (0.50)	2.1 (0.39)	0.338	0.085	0.002
Duration of flexion momentum phase (s)	0.48 (0.13)	0.52 (0.17)	0.49 (0.23)	0.45 (0.19)	0.084	0.557	0.275
Relative flexion momentum phase (%)	25 (4.4)	22 (4.9)	20 (5.9)	19 (7.2)	0.006	0.169	0.055
Acceleration of COM							
Minimal Ay (m/s ²)	−0.88 (0.21)	−0.9 (0.18)	−0.99 (0.21)	−0.88 (0.27)	0.241	0.317	0.411
Maximal Ay (m/s ²)	0.07 (0.12)	0.1 (0.04)	0.08 (0.10)	0.13 (0.19)	0.154	0.251	0.965
Range Ay (m/s ²)	0.96 (0.16)	0.99 (0.15)	1.08 (0.17)	1.01 (0.17)	0.015	0.475	0.439
Minimal Az (m/s ²)	−1.47 (0.37)	−1.60 (0.46)	−1.07 (0.28)	−1.1 (0.22)	0.000	0.905	0.953
Maximal Az (m/s ²)	1.41 (0.31)	1.32 (0.33)	1.16 (0.37)	1.51 (0.74)	0.687	0.084	0.108
Range Az (m/s ²)	2.88 (0.49)	2.93 (0.71)	2.23 (0.53)	2.62 (0.91)	0.058	0.386	0.272

Values are means (standard deviations) of seven complete data sets. Abbreviations: Ay; horizontal acceleration, Az; vertical acceleration.

Bold type setting indicates that the values was statistically significant. Load* Strategy refers to the statistical interaction of the factors load and strategy.

3.2. Strategy

The Stab-forced and Stab-natural-L conditions were characterized by an 11° increased hip-joint flexion in comparison with MomT-forced-L and MomT-natural condition ($p < 0.001$, Table 2).

3.3. Accelerations of the body centre of mass

Under the loaded conditions the range of for-aft acceleration of the CoM increased significantly (Table 1). Moreover, adding mass reduced the minimal vertical acceleration significantly. Strategy did not affect the accelerations of the CoM.

3.4. Dynamic characteristics

All dynamic variables, net joint moments, powers, impulses and work, displayed a similar redistribution over adjacent joints as a function of adding mass and changing STS-strategy. Adding 45% of body mass significantly reduced these variables for the hip and ankle joint and significantly increased the values at the knee joint. When the strategy changed from moment-transfer to stabilization an opposite redistribution occurred: significantly higher values for the hip and ankle joint and a significant reduction at the knee joint (Table 2).

4. Discussion

This study tested the hypothesis that an STS strategy-change occurs to unload a specific muscle group that becomes overloaded in the momentum-transfer-strategy. This required two questions to be answered. The first question was whether a particular muscle group did become excessively loaded when muscle weakness developed. Translated to the present approach this would mean that a particular muscle group became overloaded if extra mass was added. The second question was whether a strategy change unloaded that muscle group. The results of this study suggested that the knee-joint extensors became overloaded when body mass was increased. A strategy shift from moment-transfer to stabilization-strategy in the loaded conditions occurred to spare these muscles.

Increased loading of the knee-joint extensors was shown from a comparison between the moment-transfer-strategy under the normal and the loaded condition. This comparison showed that in the loaded condition especially the relative (mass-normalized) effort of the knee joint extensors increased substantially (maximal joint moment (13%), maximal power (10%), impulse (68%) and work (35%), Table 2). On the contrary, relative loading of hip-joint extensors and plantar flexors was lower. These data suggest that the increased effort of the STS-movement under the loaded condition was accomplished by the knee-joint extensors; while hip-joint extensors and plantar flexors were spared.

Table 2
Body-mass normalized maximal values of joint moments, joint powers, impulses and work.

	Conditions				P-values		
	MomT-natural	Stab-forced	MomT-forced-L	Stab-natural-L	Load	Strategy	Load* Strategy
Ankle joint							
Maximal plantar flexion moment (Nm/kg)	0.81(0.33)	1.42(0.18)	0.55(0.11)	0.92(0.26)	0.009	0.001	0.035
Maximal power (W/kg)	0.42(0.19)	0.74(0.20)	0.19(0.10)	0.33(0.20)	0.005	0.014	0.030
Impulse (Nms/kg)	0.76(0.39)	1.76(0.47)	0.45(0.15)	0.81(.40)	<0.001	0.002	0.019
Work (J/kg)	0.16(0.07)	0.26(0.05)	0.06(0.07)	0.10(.07)	0.001	0.023	0.230
Knee joint							
Maximal extension moment (Nm/kg)	1.85(0.36)	1.58(0.34)	2.09(0.29)	1.96(0.49)	0.001	0.017	0.307
Maximal power (W/kg) max	2.42(0.74)	1.44(0.56)	2.65(0.67)	2.64(0.61)	0.004	0.012	0.022
Impulse (Nms/kg)	1.16(0.41)	0.81(0.26)	1.98(0.64)	1.51(0.28)	0.001	0.021	0.523
Work (J/kg)	1.30(0.46)	0.64(0.20)	1.75(0.36)	1.42(0.31)	<0.001	0.003	0.072
Hip joint							
Maximal extension moment (Nm/kg)	1.64(0.28)	1.83(0.42)	1.08(0.42)	1.70(0.23)	0.005	0.010	0.164
Maximal power (W/kg)	2.32(0.33)	3.28(0.74)	1.25(0.36)	1.97(0.44)	0.001	0.002	0.503
Impulse (Nms/kg)	0.93(0.17)	1.80(0.36)	0.60(0.34)	1.16(0.47)	0.001	0.002	0.068
Work (J/kg)	1.02(0.13)	1.71(0.17)	0.56(0.24)	1.05(0.26)	<0.001	<0.001	0.106
Minimal hip angle (degrees)	83.1(9.2)	75.6(6.9)	81.9(6.9)	67.0(7.4)	0.033	<0.001	0.046

Values are means ($\pm$ sd) of seven complete data sets.

Bold type setting indicates that the values was statistically significant. Load* Strategy refers to the statistical interaction of the factors load and strategy.

To determine whether a strategy change would unload this particular muscle group, movement characteristics of both loaded conditions were compared. When the stabilization-strategy was performed in the loaded condition knee-joint extensors were spared to some extent (maximal extending mass-normalized moment (–6%), impulse (–24%) and work (–19%); maximal mass-normalized knee-joint power was not affected, (Table 2), and extra effort was required from the hip-joint extensors (maximal mass-normalized joint moment (57%), maximal power (58%), impulse (93%) and work (88%), (Table 2), compared to applying the movement in the moment-transfer-strategy. Also the effort of plantar flexors increased; however the absolute increase in loading of this muscle group was considerably smaller than that of the hip joint extensors. This suggests that under the stabilization-strategy, effort is redistributed from knee-joint extensors to hip-joint extensors. These results and the voluntary strategy shifts to the stabilization-strategy when the load is increased, support the idea that increasing the load/capacity ratio would load knee-joint extensors close to or over their limits if the strategy would not be changed, and that to prevent this an alternative strategy is chosen.

An interesting question is why the stabilization-strategy was not preferred in the unloaded condition. Previous studies suggested that the stabilization strategy provides a more stable condition while rising [2,15,16]. However, this idea does not seem to be supported by the acceleration patterns of the present study. The range of the accelerations in the horizontal plane was significantly affected by the load/capacity ratio, but not by the strategy. Also in the vertical direction no influence of strategy occurred. So this would suggest that 'stabilization-strategy' is not a proper term.

The total effort to perform the stabilization-strategy might be the reason not to prefer this strategy in the unloaded condition. The present study showed that the lower mass-normalized, maximal knee-joint extension moment that occurred when the stabilization strategy was imposed, was accompanied by a considerably higher mass-normalized, maximal ankle plantar flexion moment and a somewhat increased mass-normalized, maximal hip-joint extension moment. But may be more interesting was the increased mass-normalized total impulse that had to be generated at the ankle, knee and hip joint when the stabilization-strategy was imposed in the unloaded condition; compared to the MomT-natural condition it increased significantly from 2.84 Nms/kg to 4.36 Nms/kg. This indicates that the stabilization-strategy required more effort from the muscles than the moment-transfer-strategy. In the loaded condition the limitation of the maximal knee-joint extension moment overrules this. As the required impulse can be applied over a longer period in the stabilization-strategy, the peak joint moments can be kept within the limits of the maximal muscle capacity available.

A final intriguing question is, why hip-joint extensors and plantar flexors were 'allowed' to contribute relatively less, and knee-joint extensors had to contribute more when overall load increased. A reasonable explanation is that the GRF-vector has been directed closer to these joints, and that consequently the gear ratio [17] was affected. Future studies might address the movement coordination rules that are obviously behind this.

Although the approach of this study is to our knowledge unique, its findings are comparable to previous studies. The pattern of redistribution of joint moments that occurred in this study with changing the STS strategy was identical to redistribution patterns reported by Doorenbosch et al. [16] who compared both strategies in unloaded conditions. Also the redistribution from knee to hip that we found for both preferred strategy conditions matched with data by Schultz et al. [15].

Hughes et al. [9] suggested that in elderly a strategy change was required as the knee-joint extensors operate close to their maximal in the moment-transfer-strategy. Results of this study seem to

confirm that. Under MomT-forced-L the extending knee-joint moment was 185 Nm. Maximal isometric strength of this muscle group for a similar population has been reported to be at about the same level [18].

The choice of 45% extra load to represent muscle weakness resembles literature data. In a review Doherty [19] reported the loss of contractile strength in elderly to range between 20 and 40%. Increasing the load by 45% affects the load/capacity ratio similarly as decreasing the capacity by 31%. Moreover in previous experiments comparing the effects of 0%, 15%, 30% and 45% extra bodyweight, the 45%-condition resulted in a clear switch of strategy [12]. So the 45% extra mass is both from an experimental point of view enough to elicit a strategy change and from a clinical point of view in accordance with average levels of muscle weakness. Yet it has to be noticed that difference with respect to real, absolute muscle weakness do exist. In real muscle weakness not all muscles are affected to the same degree [20]; a difference in muscle fibre distribution and fibre specific wasting might underlie this. Moreover, in real life muscle weakness occurs gradually, allowing people to adapt to it and to develop compensatory mechanisms. The simulated change of the load/capacity ratio applied in this study is an acute effect. However, the aim of this study was not to simulate exactly muscle weakness, but rather to evaluate the isolated effect of both an increased load/capacity ratio and strategy change on loading of specific muscle groups. The invoked strategy change and the associated redistribution of joint moments that were found in this study mimic well those of studies comparing people with muscle weakness and healthy controls. This can be seen as an indication that increasing the load/capacity ratio is a major component in the adaptation seen in people with muscle weakness.

It can be concluded that increasing the load/capacity ratio in STS especially overloads the knee-joint extensors. A strategy shift from moment-transfer to stabilization-strategy in the loaded conditions occurs to spare the knee-joint extensors. Generalization of the results of this simulation study in healthy females to interventions for elderly and other groups with limited STS-capacity would suggest that strengthening of knee-joint extensors should be a component of therapy.

5. Conflict of interest

None of the authors had a conflict of interest.

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