ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Clinical Biomechanics xxx (2007) xxx–xxx

CLINICAL BIOMECHANICS

www.elsevier.com/locate/clinbiomech

Asymmetric leg loading during sit-to-stand, walking and quiet standing in patients after unilateral total hip replacement surgery

V.L. Talis [a,*], A.A. Grishin [a], I.A. Solopova [a], T.L. Oskanyan [b], V.E. Belenky [b], Y.P. Ivanenko [c]

[a] *Laboratory of Neurobiology of Motor Control, Institute for Information Transmission Problems, Russian Academy of Science, Bolshoy Karetny 19, Moscow 127994, Russia*

[b] *Department of Clinical Biomechanics, Central Clinical Hospital, Russian Academy of Science, Litovsky bulvar 1a, Moscow, Russia*

[c] *Department of Neuromotor Physiology, IRCCS Fondazione Santa Lucia, via Ardeatina 306, Rome 00179, Italy*

Received 15 May 2007; accepted 16 November 2007

Abstract

Background. Asymmetric limb loading persists well after unilateral total hip replacement surgery and represents a risk of the development of osteoarthritis in the non-operated leg. Here we studied bilateral limb loading in hip arthroplasty patients for a variety of everyday activities.

Methods. Twenty-seven patients and 27 healthy age-matched control subjects participated in the study. They were asked to stand up from a chair, to stand quietly, to perform isometric maximal voluntary contractions and to walk along a 10 m path at a natural and fast speed. Two force platforms measured vertical forces under each foot during quiet standing and sit-to-stand maneuver. Temporal variables of gait were measured using footswitches.

Findings. In all tasks patients tended to preferentially load the non-operated limb, though the amount of asymmetry depended on the task being most prominent during standing up (inter-limb weight bearing difference exceeded 20%, independent of speed or visual conditions). In contrast, when performing maximal voluntary contractions, or during walking and quiet standing, the inter-limb difference in the maximal force production, stance/swing phase durations or weight bearing was typically less than 10%.

Interpretation. The results suggest that the amount of asymmetry might not be necessarily the same for different tasks. Asymmetric leg loading in patients can be critical during sit-to-stand maneuver in comparison with quiet standing and walking, and visual information seems to play only a minor role in the control of the weight-bearing ability. The proposed asymmetry indices might be clinically significant for development of post-surgical rehabilitation.

Keywords: Hip arthroplasty; Asymmetry; Loading; Sit-to-stand; Posture; Locomotion; Humans

1. Introduction

The total hip arthroplasty (THA) is a surgical procedure that usually results in a marked decrease in pain and in a concomitant improvement of the functional capacity of patients. However, despite the pain relief on the operated side and hardly noticeable changes in the hip joint position sense (Karanjia and Ferguson, 1983), in many cases motor abilities do not achieve the normal level (Sicard-Roesnbaum et al., 2002; Vogt et al., 2003; Miki et al., 2004). Walking speed remains below the normal values up to 2–4 years following the surgery (Perron et al., 2003). Gait slowness is accompanied by a significant decrease in the extensor moment of force during early stance, reduced range of hip extension and increased anterior pelvic rotation, knee flexion and ankle dorsiflexion during walking (McCrory et al., 2001). Asymmetric inter-limb coordination has a risk of overloading the non-operated hip joint,

* Corresponding author.
E-mail address: VeraTalis@yahoo.com (V.L. Talis).

0268-0033/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2007.11.010

which in turn may lead to the development of osteoarthritis in this leg (in about 15–20% of patients, Suter et al., 1998) or to the risk of a fall, especially in the elderly (Majewski et al., 2005).

Walking, sit-to-stand movement and quiet standing are basic motor activities. Walking is a standard test to assess a functional deficit in patients with THA. The weight bearing asymmetry during walking can be assessed indirectly as a lateral shift in the center-of-mass position (Sliwinski et al., 2004), difference of vertical ground reaction force in the affected leg (McCrory et al., 2001), or measuring the angular trunk motion (Majewski et al., 2005). In comparison to gait, sit-to-stand maneuver can be considered to be physiologically more demanding since movements of larger amplitude and greater forces of proximal muscles (in particular, lumbar paraspinal, quadriceps and hamstrings, Goulart and Valls-Sole, 1999) are required to lift the body weight (Su et al., 1998). This task is also performed under the conditions of relatively small support surface, i.e. it can be considered as a dynamical equilibrium task. Sit-to-stand movement was intensively investigated in elderly subjects (Mourey et al., 2000), as well as in people with Parkinson's disease (Mak et al., 2003), stroke (Eng and Chu, 2002) and paraplegic (Bahrami et al., 2000) patients. These studies have demonstrated both modifications in the temporal organization and in the amplitude of motor responses and correlation between difficulties in performance of sit-to-stand movement and balance disorders. Reports on sit-to-stand and quiet standing in THA patients are quite scarce. Namely, it was found that 'standing up from a chair and walking 3 m' test was done significantly slower in THA patients than in healthy subjects (Perron et al., 2003) and that specific training can improve sit-to-stand performance (Drabsch et al., 1998).

Asymmetric limb loading following THA can be classified as a 'complication' following surgery as it may impact on function and quality of life. Combining tests with progressive levels of difficulty, such as quiet standing, walking and sit-to-stand tests, may be critical for development of effective training and rehabilitation intervention for physical therapists (e.g., in stroke patients, Eng and Chu, 2002). The purpose of the present study was to investigate asymmetric limb loading in THA patients during quiet standing, walking and standing up from a chair, in order to evaluate the amount of functional deficit in different tasks and to compare the magnitude of weight-bearing asymmetry in THA patients and in healthy subjects. We hypothesized that the amount of weight bearing asymmetry might be more pronounced during sit-to-stand movement as it is a physiologically more demanding task. To explore further different conditions, the test was performed both at a natural speed and as fast as possible. In addition, we aimed to study the effect of vision on weight-bearing asymmetry. Tests with eyes closed are known to be more 'provocative' than tests performed with eyes open. A potentially stronger effect on the asymmetry could thus be expected for eyes-closed tests compared with eyes-open tests, especially in more challenging conditions such as sit-to-stand movements. Visual information may significantly improve movement performance in deafferented patients (see, for instance, Ghez et al., 1995; Lajoie et al., 1996), as well as eyes closure may destabilize posture resulting in a significant increase of body weight distribution asymmetry in the elderly (Blaszczyk et al., 2000). However, little is known about whether use of vision improves asymmetry indexes in THA patients. To this end, we compared bilateral limb loading in patients when the task was performed in eyes-open and eyes-closed conditions.

2. Methods

2.1. Participants

Twenty-seven patients with unilateral hip replacement (20 females and seven males; mean age 56 (SD 10) (34–76) years; height 165 (SD 8) cm; weight 76 (SD 10) kg, mean time after surgery – 19 months) participated in this study (Table 1). The indication for surgery for patients was degenerative arthritis of the hip. Twenty-seven healthy age–weight–height-matched subjects served as controls (18 females, nine males; mean age 55 (SD 9) (35–68) years; height 168 (SD 8) cm; weight 70 (SD 12) kg). Healthy subjects were medical personal of the hospital and the authors. Subjects were excluded if they had had surgery for the lower limbs or had other medical conditions preventing them from completing the tests. Selection of the patients was based on their ability to perform the tasks (stand up from a chair and walk along a 10 m path without aid). It should be noted, that nine patients used a cane during outdoor walking, but using the cane was not related to the time after surgery (Table 1) and these patients were able to perform the sit-to-stand and walking tests without using the cane. Patients were further excluded with hip replacement secondary to an infection or a revision and on the basis of inequality in left and right leg length of greater than 1 cm. Leg length was measured as the distance between the superior anterior spine of the iliac bone and the medial malleolus, while the subject was lying relaxed in the supine position. Patients, who had significant pain in the contralateral hip and knee joints (>5 points, according to the 10 point visual analogue scale) were also excluded (Table 1). The procedures were approved by the review body of the Central Clinical Hospital and conformed with the Declaration of Helsinki. Each individual was informed of the study procedures before their consent to participate in the study.

2.2. Data acquisition and test procedures

The protocol consisted of a series of activities divided into four tasks in the following order: maximal voluntary contractions, quiet standing, standing up from a chair and walking. The total duration of the experimental session was ~1 h with a rest period of 5–10 min between the tasks.

Table 1
Baseline characteristics of patients with unilateral hip replacement

Patient	Age (years)	Sex	Weight (kg)	Height (cm)	Duration of disease before surgery (years)	Time since surgery	Operated side	Cane	State/pain[a] on the day of investigation
P1	34	M	90	174	3	2 months	L	+	Arthrosis of the right hip/no pain
P2	45	M	75	180	10	1.5 months	L	+	Arthrosis of the right hip/no pain
P3	69	F	71	164	7	2 year	L	+	Arthrosis of the right hip and knee /4–5
P4	60	F	65	168	4	4 year	L	–	Arthrosis of the right hip/ no pain
P5	67	F	67	154	15	3 months	L	+	Arthrosis of the right hip/3
P6	63	F	64	157	2	6 months	L	–	No pain
P7	62	F	63	165	3	1.8 year	L	+	Arthrosis of the right hip/3
P8	51	F	82	163	5	3 months	L	–	Arthrosis of the right hip /2
P9	49	F	78	156	5	2.8 year	L	–	Arthrosis of the right hip /1
P10	37	F	84	166	5	2.5 year	L	–	Arthrosis of the right hip /4
P11	65	M	88	175	3	1 year	R	–	No pain
P12	56	F	75	177	5	10 months	R	–	No pain
P13	60	F	85	156	3	10 months	R	–	Arthrosis of the left knee /4
P14	54	F	88	174	2.5	1.2 year	R	–	Pain in the lumbar spine /1
P15	57	M	67	174	10	2 year	R	–	No pain
P16	54	F	82	170	5	6 months	R	+	No pain
P17	52	F	90	174	20	9 months	R	–	Arthrosis of the left knee, hip/ 3
P18	61	M	74	175	3	9 months	R	+	Pain in the left ankle /2
P19	61	F	74	154	4	1.3 year	R	+	Pain in the lumbar spine /1
P20	55	F	82	160	4	1.5 year	R	–	No pain
P21	52	F	72	165	2	9 months	L	–	No pain
P22	60	F	53	159	15	3.7 year	L	–	Arthrosis of the right hip /5
P23	63	M	65	170	2	3.3 year	L	–	No pain
P24	71	F	88	165	5	3.3 year	R	+	Arthrosis of the left hip /3
P25	46	M	85	172	1	9 months	L	–	Pain in the right ankle /4
P26	44	F	85	156	1	3.7 year	L	–	No pain
P27	76	F	65	150	3	2.8 year	L	–	Pain in the lumbar spine /5

[a] Pain on the day of investigation was measured using a 10-point visual analogue pain score (0 – none, 3–4 – moderate, 5–6 – strong, 9–10 – severe).

2.3. Measurement of the maximal voluntary moment of force of knee flexors/extensors and hip abductors/adductors

We measured isometric maximal voluntary contractions (MVC) of knee flexors, knee extensors, hip abductors and hip adductors in both legs. Knee extensors participate conspicuously in standing up movement (Goulart and Valls-Sole, 1999) and some knee flexors/extensors are also biarticular (hip) muscles. Force recordings of hip adductors and abductors were performed because of their potential contribution to the lateral stability and weight-bearing asymmetry during walking (Sliwinski et al., 2004) and quite standing (Jeka and Lackner, 1995). Hip arthrosis can be also accompanied by a decrease of strength of the abductor muscles (Belenky et al., 2004). Measurements in patients started with the non-operated leg. The subjects were asked to maintain maximal effort for about 3–5 s. Strong verbal encouragement was given during each trial.

To measure the moment of force in knee flexors and extensors, subjects were seated with their arms placed on a rigid support in front of the body, thighs were horizontal and the knee joint was ~70°. The distal part of the shank segment (near the ankle joint) was fixed firmly and the horizontal force was measured by means of strain gauge sensors (2PCB-10-200 Topkino, Russia) attached to a stationary frame. The calibration of the instrument was tested prior to the measurements using the standard weights (accuracy 1 N). The length of the shank segment and the angle of knee flexion were used to calculate the arm of the force. To measure the isometric moment of force of hip adductors/abductors, we used a procedure similar to that described by Andrews et al. (1996) and Chang et al. (2005). The subject was positioned supine on a padded table with arms placed across the chest and both legs in a neutral position with respect to hip internal and external rotation and adduction and abduction. The distal part of the shank segment was fixed to the stationary frame via a strain gauge sensor (Belenky et al., 2004). Subjects were instructed to keep the leg straight and push or pull the leg, and the horizontal force in the desired direction was recorded at 100 Hz. A research assistant stabilized the contralateral leg in a neutral position during testing. The length of the shank+thigh segment was used to calculate the arm of the force. The maximum force value obtained in three attempts, with a 1 min rest period between trials, was used for calculation of the maximal voluntary moment of force.

For patients, we used the following asymmetry index:

$$A_M = (M_N - M_O)/(M_N + M_O) * 100\% \quad (1)$$

where M_N and M_O are the moments of force in the non-operated and operated legs, respectively.

For controls, we used the absolute values of A_M, such that, for each subject, the asymmetry index was always positive:

$$A_M = \text{abs}((M_1 - M_2)/(M_1 + M_2)) * 100\% \quad (2)$$

where M_1 and M_2 are the moments of force in the right and left leg, respectively. Possibly this method (Eq. (2)) slightly overestimates the actual mean asymmetry index in controls, since random fluctuations around zero would accumulate when averaging A_M across subjects, however, it represents a reasonable way for estimating the upper limit of mean asymmetry in the population of healthy humans (see, for instance, Marigold and Eng, 2006).

2.4. Quiet standing

During quiet standing (barefoot) the feet of the subject were placed on separate stabiloplatforms, with the heels spaced 10 cm apart. Thus, the bilateral loadings were measured directly and independent of the varus/valgus moments. Subjects were instructed to stand naturally for 40 s with their arms at their sides: 20 s with eyes open (EO) and 20 s with eyes closed (EC). No other specific instructions were given. Three trials were recorded. The mean vertical forces under each foot (300 Hz sampling rate) were computed during 20 s of standing with eyes open and eyes closed and a postural asymmetry index was calculated analogous to that of the MVC

$$A_p = (F_{ZN} - F_{ZO})/(F_{ZN} + F_{ZO}) * 100\% \quad \text{for patients} \quad (3)$$

and

$$A_p = \text{abs}((F_{Z1} - F_{Z2})/(F_{Z1} + F_{Z2})) * 100\% \quad \text{for controls} \quad (4)$$

where F_{zi} is the mean vertical force (across three trials) of the appropriate force platform.

2.5. Sit-to-stand movement

Subjects were seated on an armless chair (without a back support) whose height was adjusted to keep the thigh horizontal (Fig. 1A). The feet were placed on separate force

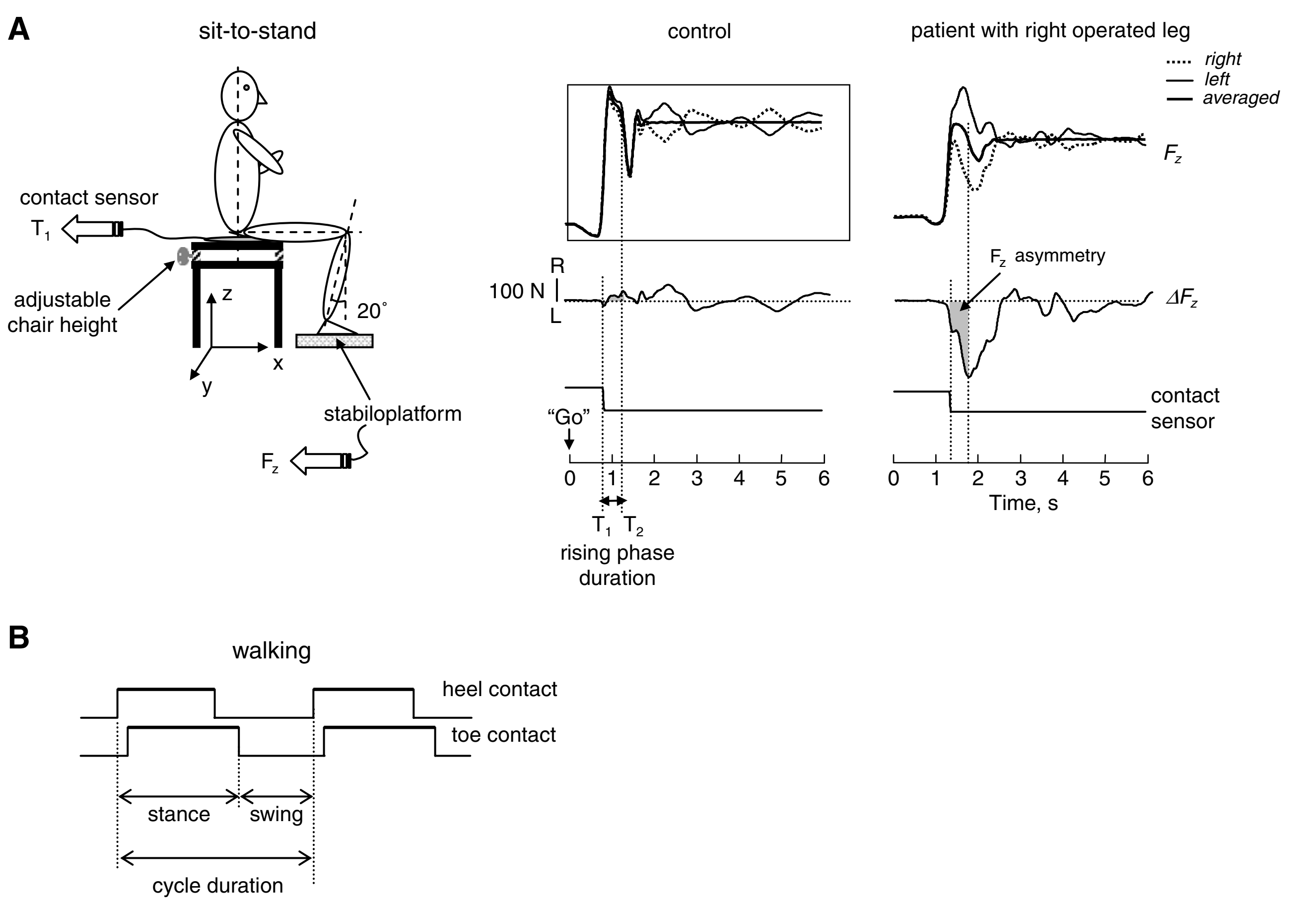

Fig. 1. Experimental set-up. (A) sit-to-stand. The instant of seat-off (T_1) and force plate signals (F_z) were measured. Examples of sit-to-stand recordings in one control subject and one THA patient are shown in the right panels. From top to bottom: vertical forces under each foot and the averaged force, the difference between them (ΔF_z) and the contact sensor signal. The end of the rising phase T_2 was calculated as the time when the total vertical force crossed for the second time a threshold level, corresponding to the subject weight. The shaded area of ΔF_z (divided by the movement duration) characterized asymmetric leg loading during the rising phase of standing up. (B) calculation of the stance and swing durations during walking. Foot contact events were measured using two footswitches taped to the toe and heel of each shoe. The heel footswitch was used to determine the touchdown event while the toe footswitch was used to determine the lift-off event.

Please cite this article in press as: Talis, V.L. et al., Asymmetric leg loading during sit-to-stand, walking and quiet ..., J. Clin. Biomech. (2007), doi:10.1016/j.clinbiomech.2007.11.010

plates, with the heels spaced 10 cm apart being the same as in the quiet standing task. Shank orientation constituted a 20° angle with the vertical. Before the recording session, subjects were given two practice trials. Subjects were instructed to rise from a chair as they would usually do except without using the arms. The arms were folded on the chest and the subjects were instructed to maintain the same initial natural vertical trunk position. An acoustic tone served as a trigger ('go') signal to stand up. Subjects (barefoot) executed this movement at natural speed with eyes open (EO), as fast as possible (fast) and at natural speed with eyes closed (EC) (three trials in each condition). The natural speed EO condition was always the first one and a sequence of the two other blocks was randomized across subjects. Between the blocks subjects were given a rest period of approximately 2 min.

Data were acquired for 6 s at a sampling rate of 300 Hz with a 16-bit A/D converter connected to a computer. The force plate data were filtered using a Butterworth fourth-order low-pass filter (cutoff 6 Hz). The total value of the vertical force ($F_z=F_{z1}+F_{z2}$) for the last 2 s of the trial indicated the subject's weight. The instant of rising up from the chair (T_1) was measured by means of a pneumatic (pressure) contact sensor placed on the chair-bottom (Fig. 1A). The end of the vertical acceleration phase (T_2) was computed as the time when F_z crossed for the second time a threshold level, corresponding to the subject weight (Fig. 1A). Standing-up dynamic asymmetry A_s was computed during the period from T_1 to T_2 using the same equations as for the MVC and postural asymmetry. We chose this period since it corresponds to the maximal force production and maximal vertical acceleration of the centre of mass (CoM) during sit-to-stand movement (Mourey et al., 2000; Roy et al., 2006).

2.6. Walking

Subjects (with special light shoes on) were asked to walk unaided along a 10-m walkway: three times at their natural speed and three times as fast as possible. They were asked to swing the arms alongside the body. Mean walking speed was determined using photocells placed 8 m apart along the walkway. Contact events (heel strike and lift-off) were measured (at 140 Hz) using four pressure-sensitive footswitches (1 mm thick) placed inside both shoes and taped to the heel and toe regions. The shoes were light with a minimal heel height (8 mm) and unlikely affected the asymmetry of walking. The heel footswitch was used to determine the heel strike event while the toe footswitch was used to determine the lift-off event (Fig. 1B). The relative duration of the swing phase (Fig. 1B) expressed as a percentage of gait cycle was used for side-to-side comparison of temporal asymmetries (see also Ouellet and Moffet, 2002).

2.7. Statistics

Descriptive statistics included means and standard deviation (SD) of the mean of the following variables: asymmetry indices in all tasks, maximal isometric voluntary efforts, walking speed and sit-to-stand movement duration. A 2×2 or 2×3 ANOVA (group × condition) was used to get main effects and interactions. Post-hoc tests were performed by using the Tukey test. For quiet standing and standing up tests, we performed ANOVA on the asymmetry indexes, while for MVC and walking tests, we also analyzed and plotted the data for both legs to assess the absolute values of isometric voluntary contractions or swing phase durations. Non-parametric Mann–Whitney test was used to compare asymmetry indices between patients, who assisted every day walking by cane and who did not. The level of statistical significance was set at 0.05. Linear regression analysis using Pearson's correlation coefficients (r) was used to estimate relationships between asymmetry indices across different tasks.

3. Results

3.1. Maximal voluntary moment of force of knee flexors/extensors and hip abductors/adductors

There were no significant differences in the MVC between controls and patients for knee flexors and for adductors/abductors. However, a 2×2 ANOVA (limb × group) showed significant difference in the knee extensors ($F(1, 52) = 7.53$, $P < 0.01$) and interaction ($F(1, 52) = 5.39$, $P < 0.02$). The post-hoc Tukey test showed that in patients the knee extensors on the operated side were weaker ($P < 0.05$, Table 2): the maximal moment of force of the knee extensors of the operated leg was significantly lower than that of the non-operated leg (by about 14%) and the asymmetry index was 9.3% (SD 17.3) (4.8% (SD 3.2) in controls). The maximal moment of force of other muscle groups of the operated leg did not significantly differ from that of the non-operated leg (Table 2).

Table 2
Maximal voluntary moment of force, N m, and asymmetry index (A_M), %, in knee flexors, knee extensors, hip abductors and hip adductors in THA patients (O – operated leg, N – non-operated leg), [mean(SD)]

Knee flexors			Knee extensors			Hip abductors			Hip adductors		
N	*O*	A_M	*N*	*O*	A_M	*N*	*O*	A_M	*N*	*O*	A_M
47(22)	46(22)	1.3(16.2)	64(25)	55(26)[a]	9.3(17.3)	54(31)	49(32)	7.2(15.5)	58(25)	59(32)	3.0(11.4)

[a] $P < 0.05$ in comparison with the contralateral leg.

Please cite this article in press as: Talis, V.L. et al., Asymmetric leg loading during sit-to-stand, walking and quiet ..., J. Clin. Biomech. (2007), doi:10.1016/j.clinbiomech.2007.11.010

3.2. Quiet standing

During quiet standing, the asymmetry index A_p in control subjects was 7.6% (SD 6.3) and 8.2% (SD 5.9) in EO and EC conditions, respectively. Variability in A_p likely reflected normal variability in the lateral centre-of-pressure position and/or variability of the spine and pelvis location with respect to the gravity line in control subjects during upright posture (Schwab et al., 2006) that may result in uneven partitioning of the body mass on each side. There was no significant difference between postural asymmetry indexes in healthy subjects and patients (2 × 2 ANOVA, $F(1, 52) = 1.48$, $P = 0.22$). A_p in control subjects did not depend on condition (EO vs EC, $F(1, 52) = 0.87$, $P = 0.35$). Nevertheless, the majority of THA patients tended to load the non-operated leg (A_p was on average 12.0 (SD 16.4) in EO and 10.1% (SD 14.2) in EC). Yet, two patients (P1 and P20, Table 1) showed the opposite effect: they systematically (across 3 trials) loaded the operated leg ($A_p \sim -6\%$).

3.3. Walking

The normal and fast walking speeds in patients (1.1 (0.2) and 1.4 m/s (0.3), respectively) were significantly slower than those in control subjects (1.2 (0.2) and 1.7 m/s (0.3)) (2 × 2 ANOVA (group × speed), $F(1, 52) = 23.3$, $P < 0.00001$). In patients, the swing phase duration of the non-operated leg was shorter than that of the operated leg during walking both at the natural and fast speed (ANOVA $F(1, 52) = 15.73$, $P < 0.0002$) (Fig. 2). In other words, the non-operated leg was loaded for a longer period of time than the operated one.

3.4. Standing up from a chair

Fig. 3A shows typical examples of bilateral limb loading (ΔF_z) during sit-to-stand movement in five control subjects and ten patients (five patients with right operated leg and five patients with left operated leg). Sit-to-stand movement is a stereotyped behavior: prior to seat-off (T_1), the trunk starts to flex forward, the centre-of-pressure displaces backward and the CoM accelerates forward (Mourey et al., 2000). After the instant of seat-off, the CoM decelerates and the centre-of-pressure moves significantly forward. The CoM accelerates and decelerates upwards, which corresponds to the positive and negative F_z waves (Fig. 1A), and at the end of movement F_z returns to the stationary level, corresponding to the subject's weight.

The movement duration was roughly similar in controls and patients. In control subjects, it was 0.61 (SD 0.23), 0.45 (SD 0.16) and 0.59 (SD 0.19) in EO, fast and EC conditions, respectively, and in patients – 0.71 (SD 0.25), 0.50 (SD 0.18) and 0.63 s (SD 0.24), respectively. Control subjects tended to perform all sit-to-stand movements slightly faster than patients but this difference was not significant ($P = 0.75$). Both control subjects and patients significantly decreased the movement duration in the fast condition in comparison with EO and EC conditions. Asymmetric limb loading was present in patients in all sit-to-stand conditions (Fig. 3B), being significantly higher than in controls (2 × 3 ANOVA (group × condition) $F(1, 52) = 33.1$, $P < 0.0002$). The amount of asymmetry did not depend on condition both in patients and in control subjects ($F(2, 104) = 1.36$, $P = 0.25$, interaction between factors $F(2, 104) = 0.05$, $P = 0.95$). The direction of asymmetry clearly depended on the side of the hip arthroplasty with more weight shift on the non-operated side (Fig. 3A) (mean A_s was 21.9% (SD 12.8) across all conditions). In patients, asymmetric limb loading was significantly higher during sit-to-stand motion (A_s) than that during quiet standing (A_p) both in EO and EC conditions (2 × 2 ANOVA (task × condition) $F(1, 52) = 42.6$, $P < 0.00001$).

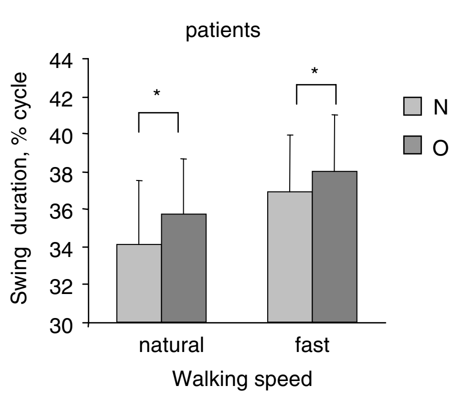

Fig. 2. Swing phase durations of both legs during walking at a natural and fast speed in THA patients. O – operated leg, N – non-operated leg. * – $P < 0.05$ in comparison with the contralateral leg.

3.5. Comparison of weight-bearing asymmetry across tasks and patients

As we described before (Table 2), the MVC of knee extensors was less for the operated leg. Nevertheless, force deficit of the knee extensors in patients showed only weak correlation with sit-to-stand asymmetry A_s ($r = 0.22$), postural asymmetry A_p ($r = 0.14$) or with the asymmetry of the swing phase duration during walking ($r = 0.15$).

A_s displayed also weak correlation with the asymmetry in quiet standing ($r = 0.25$) or in walking ($r = 0.31$). As an example, several patients (i.e., P9, P13, P15 and P18, Table 1) systematically showed considerable asymmetry during sit-to-stand ($A_s \sim 20$–35% in all trials), however, their gait was quite symmetrical. Two patients who systematically loaded the operated leg during quiet standing (P1 and P20, $A_p \sim -6\%$, see above) loaded the non-operated leg during sit-to-stand ($A_s \sim 20\%$). Moreover, we recorded them again, 1 month later, and they showed the same effect (positive A_s and negative A_p).

The asymmetry of standing up movement, quiet standing and walking did not show any significant difference between patients who assisted their everyday motion by

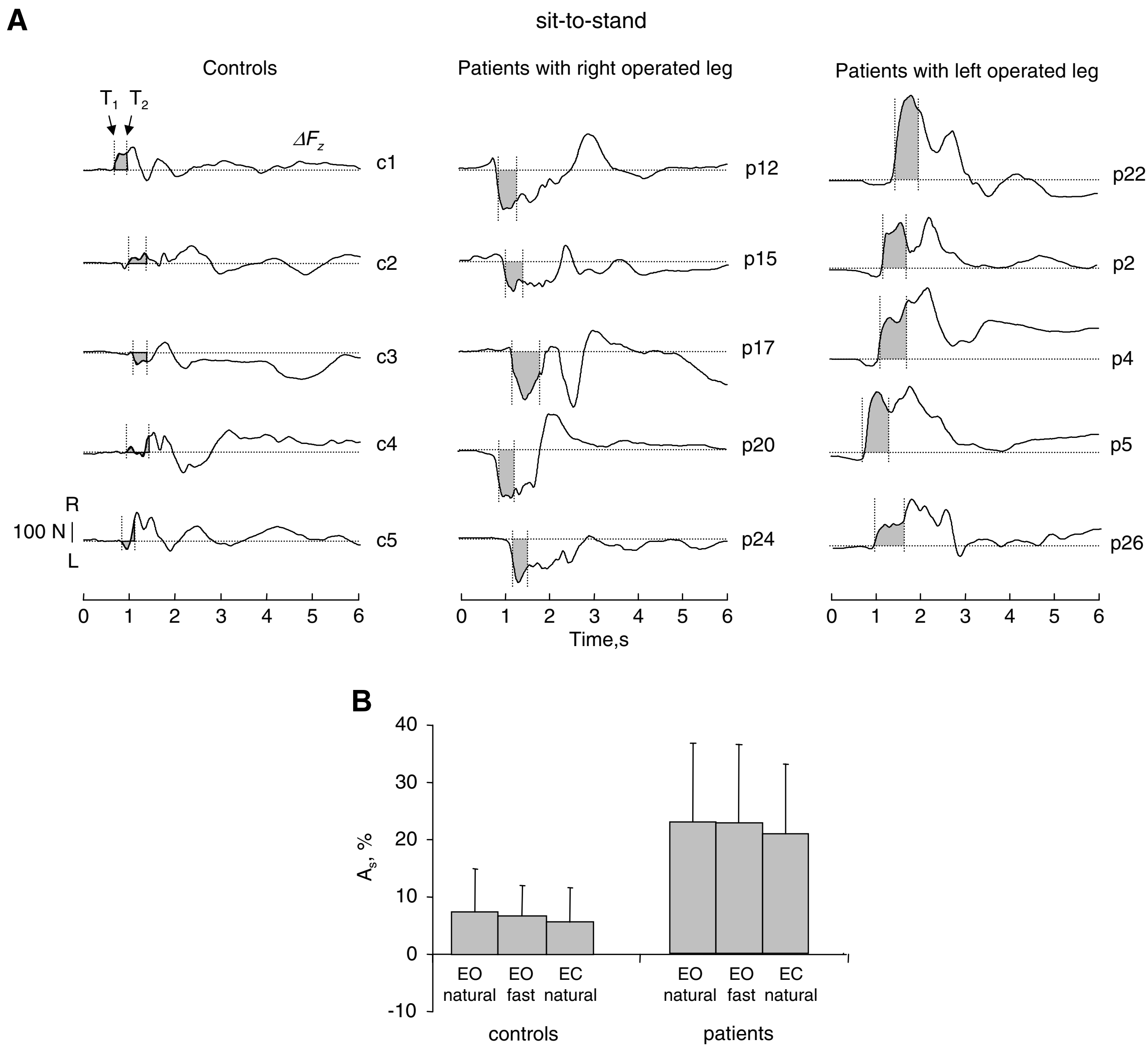

Fig. 3. Sit-to-stand results. (A) The difference in leg loadings (ΔF_z) during standing up from a chair at a natural speed with eyes open in five control subjects and 10 patients with right and left operated legs. T_1 – seat off, T_2 – the end of the rising phase. The shaded area of ΔF_z (divided by the movement duration) characterized asymmetric leg loading in patients and control subjects during standing up. (B) Sit-to-stand asymmetry (A_s, mean±SD) during natural EO, fast EO and natural EC conditions in controls and patients.

the cane ($n = 9$) and those who did not ($n = 18$, Table 1) ($P > 0.05$, non-parametric Mann–Whitney U-test). Finally, the asymmetry of standing up was not correlated with the time after surgery ($r = 0.11$). In sum, we found no parameter that unequivocally determined the amount of asymmetry in patients, supporting the idea of subject- and task-dependent bilateral loading.

4. Discussion

The results demonstrated that asymmetric inter-limb coordination persists well in various motor tasks after unilateral total hip replacement surgery, regardless of speed or visual conditions (Figs. 2 and 3). Thus, patients were predisposed to shift more weight to the non-operated leg (Fig. 3), even though some of them experienced moderate pain intensities in the non-operated leg at the time of testing (Table 1). Furthermore, asymmetry scores did not show a strong relationship with isometric force deficit of knee extensors in the prosthetic leg. We also failed to find the difference between the sub-groups of patients (time since surgery, using the cane). Thus, we conclude that the amount of asymmetry in THA patients might not be necessarily the same for different tasks.

4.1. Weight bearing on bilateral limbs

Functional ability requires weight bearing on bilateral limbs. While total loading (~body weight) was similar across the tasks studied, moments of force in individual

Please cite this article in press as: Talis, V.L. et al., Asymmetric leg loading during sit-to-stand, walking and quiet ..., J. Clin. Biomech. (2007), doi:10.1016/j.clinbiomech.2007.11.010

joints and redistribution of body weight between the limbs could be quite different. For instance, more demands are placed on the hip and knee musculature when rising from a chair (Eng and Chu, 2002) than during walking (Shakoor et al., 2003) or standing (Gurfinkel et al., 1995). In agreement with previous studies (McCrory et al., 2001; Drabsch et al., 1998), THA patients tended to walk slower than control subjects and the relative swing phase duration of the prosthetic leg was longer (Fig. 2). During walking, the asymmetry of bilateral hip muscle activation and of weight bearing is difficult to assess straightforwardly, and it might also depend on small changes in the body configuration. Nevertheless, it is tempting to speculate that the asymmetry is more pronounced in the standing up test, which reveals a remarkable difference in the bilateral limb coordination (Fig. 3).

4.2. Weight bearing control

What is the cause of asymmetric loading in THA patients? Prolonged weakness, a lack of hip joint proprioception or a habitual movement pattern adopted prior to surgery might be among the important factors that sustained a continued disuse of the operated side (McCrory et al., 2001). The extensor force deficit in the operated limb could be a limiting factor leading to underloading (Table 2). Yet, it is not possible to determine if patients favored their affected limb because they were weak, or if they were weak because they favored their affected limb. However, our data did not show high correlations between force deficit and task asymmetries in patients (as well as the averaged absolute value of A_s exceeded significantly A_M, Fig. 3B and Table 2). Likely, separate and coordinative limb behavior may rely on different rules resulting in different asymmetry scores in different tasks. In this respect, our results are in contrast to those obtained in stroke patients who showed high correlations of weight bearing asymmetry across the tasks (Eng and Chu, 2002). Possibly, stroke patients represent a more homogeneous population (with a pronounced weakness in the paretic lower limb that results in higher A_p indices than those in THA patients) while a more variable amount of weight-bearing asymmetry in THA patients could be due to several factors that interact in a complex way. In addition, Ap in THA patients could be masked somehow by normal variability of the spinopelvic alignment with respect to the gravity line that may result in uneven partitioning of the body mass on each foot even in control subjects (Schwab et al., 2006).

A lack of hip joint proprioception in the operated leg may have contributed as well to asymmetric limb loading. The importance of proprioceptive feedback from hip joint and muscle afferents is well established for the control of muscle activity and the timing of locomotor events in animals (Duysens et al., 2000). In humans, the role of hip joint afferents is much less clear, even though position sense in the hip joint is not disturbed significantly after THA surgery (Karanjia and Ferguson, 1983), likely due to the intact proprioception in the muscles surrounding the hip. Yet, diminished sensory information can make movement control more sensitive to the difficulty of the task in patients than in control subjects, as well as more cognitively dependent (Courtemanche et al., 1996). Pain in the non-operated leg would likely have been expected to accelerate ‘relearning’ of asymmetry adopted prior to surgery; however, patients were still predisposed to shift more weight to the non-operated side. Possibly, they ‘preferred’ moderate pain sensations in the non-operated leg rather than a lack of proprioceptive sensation in the contralateral limb. Thus, the argument may be made that the residual postoperative asymmetry is beneficial because the arthroplasty patients have no hip joint proprioception in their affected limb, and they are therefore perceptually more “stable” on their unaffected leg. This is partly confirmed by the subjective reports of the patients who claimed often that they “are not secure in the operated leg”.

Finally, it is quite possible that the patients learned not to load their operated lower extremity right after the surgery and continued to do so even after recovery. Such “learned” asymmetry of weight bearing could be considered as adaptive behavior that is common in other patient populations.

4.3. Effect of vision

We did not find any significant difference in asymmetric limb loading between EO and EC conditions both in control subjects and patients. One could expect that persons suffering a loss of proprioception significantly rely on vision which provides additional dynamic and body configuration information for improving motor performance (Ghez et al., 1995; Courtemanche et al., 1996; Lajoie et al., 1996). It seems therefore likely that visual information in unilateral hip arthroplasty patients could be used for controlling postural stability and/or general characteristics of movement rather than for updating the pre-existing central motor programs for weight-bearing ability during standing or sit-to-stand maneuver. Accordingly, our results suggest that visual cues play only a minor role in the control of weight bearing asymmetry in THA patients.

4.4. Limitation and clinical significance of the study

An additional stress placed on the unaffected leg might occur despite the fact that patients are strongly instructed to load the operated hip a few months after surgery, although special training is likely needed to follow this instruction. The effectiveness of voluntary loading is a matter of debate (Rodriguez and Aruin, 2002) and task-dependent neuroplasticity may underlie recovery of motor function (Winstein et al., 1989; Grasso et al., 2004). It would be useful to study the extent to which improvements in weight-bearing ability in one task might be generalized to other tasks. A clear idea of short- and long-term per-

Please cite this article in press as: Talis, V.L. et al., Asymmetric leg loading during sit-to-stand, walking and quiet ..., J. Clin. Biomech. (2007), doi:10.1016/j.clinbiomech.2007.11.010

spectives of patient recovery is important when choosing among rehabilitation programs aimed at reducing weight bearing asymmetry. For instance, the long-term consequences of incorrect rehabilitation have been shown for a group of THA patients who walked with and without crutches in early rehabilitation period after the surgery (Sonntag et al., 2000). The authors of that study argued that patients should walk unaided as soon as possible to provide more efficient training. Different symmetry descriptors are appropriate for development of post-surgical rehabilitation of arthroplasty patients. The standing-up test may be used for therapeutic purposes to monitor the weight bearing symmetry scores in the course of recovery in patients with sensory-motor disorders (after unilateral THA, hemiparetic patients, Lomaglio and Eng, 2005), since this dynamic task requires simultaneous appropriate bilateral coordinated behavior (Fig. 3). Finally, gait and sit-to-stand feedback training (perhaps combined with assisted functional electrical stimulation) may possibly be more efficient for patients' rehabilitation.

Acknowledgments

This research was supported by a grant from the RFBR No 06-04-48891 and the program "Basic science – for medicine" of the Russian Academy of Science.

References

Andrews, A.W., Thomas, M.W., Bohannon, R.W., 1996. Normative values for isometric muscle force measurements obtained with hand-held dynamometers. Phys. Ther. 76, 248–259.

Bahrami, F., Riener, R., Jabedar-Maralani, P., Schmidt, G., 2000. Biomechanical analysis of sit-to-stand transfer in healthy and paraplegic subjects. Clin. Biomech. 15, 123–133.

Belenky, V.E., Grishin, A.A., Krivosheina, E.N., 2004. Treatment of coxarthrosis by means of functional electrical stimulation. Bull. Traumatol. Orthop. 4, 20–24 (in Russian).

Blaszczyk, J.W., Prince, F., Raiche, M., Hebert, R., 2000. Effect of ageing and vision on limb load asymmetry during quiet stance. J. Biomech. 33 (10), 1243–1248.

Chang, S.H., Mercer, V.S., Giuliani, C.A., Slogane, P.D., 2005. Relationship between hip abductor rate of force development and mediolateral stability in older adults. Arch. Phys. Med. Rehabil. 86 (9), 1843–1850.

Courtemanche, R., Teasdale, N., Boucher, P., Fleury, M., Lajoie, Y., Bard, C., 1996. Gait problems in diabetic neuropathic patients. Arch. Phys. Med. Rehabil. 77 (9), 849–855.

Drabsch, T., Lovenfosse, J., Fowler, V., Adams, R., Drabsch, P., 1998. Effects of task-specific training on walking and sit-to-stand after total hip replacement. Aust. J. Physiother. 44, 193–198.

Duysens, J., Clarac, F., Cruse, H., 2000. Load-regulating mechanisms in gait and posture: comparative aspects. Physiol. Rev. 80 (1), 83–133.

Eng, J., Chu, K., 2002. Reliability and comparison of weight-bearing ability during standing tasks for individuals with chronic stroke. Arch. Phys. Med. Rehabil. 83, 1138–1144.

Ghez, C., Gordon, J., Ghilardi, M.F., 1995. Impairments of reaching movements in patients without proprioception. II. Effects of visual information on accuracy.. J Neurophysiol. 73 (1), 361–372.

Goulart, F.R., Valls-Sole, J., 1999. Patterned electromyographic activity in the sit-to-stand movement. Clin. Neurophysiol. 110, 1634–1640.

Grasso, R., Ivanenko, Y.P., Zago, M., Molinari, M., Scivoletto, G., Lacquaniti, F., 2004. Recovery of forward stepping in spinal cord injured patients does not transfer to untrained backward stepping. Exp. Brain Res. 157, 377–382.

Gurfinkel, V.S., Ivanenko, Y.P., Levik, Y.S., Babakova, I.A., 1995. Kinesthetic reference for human orthograde posture. Neuroscience 68, 229–243.

Jeka, J.J., Lackner, J.R., 1995. The role of haptic cues from rough and slippery surfaces in human postural control. Exp. Brain Res. 103, 267–276.

Karanjia, P.N., Ferguson, J.H., 1983. Passive joint position sense after total hip replacement surgery. Ann. Neurol. 13, 654–657.

Lajoie, Y., Teasdale, N., Cole, J.D., Burnett, M., Bard, C., Fleury, M., Forget, R., Paillard, J., Lamarre, Y., 1996. Gait of a deafferented subject without large myelinated sensory fibers below the neck. Neurology 47 (1), 109–115.

Lomaglio, M.J., Eng, J.J., 2005. Muscle strength and weight-bearing symmetry relate to sit-to-stand performance in individuals with stroke. Gait Posture 22, 126–131.

Majewski, M., Bischoff-Ferrari, H.A., Gruneberg, C., Dick, W., Allum, J.H., 2005. Improvements in balance after total hip replacement. J. Bone Joint Surg. Br. 87, 1337–1343.

Mak, M.K., Levin, O., Mizrahi, J., Hui-Chan, C.W., 2003. Joint torques during sit-to-stand in healthy subjects and people with Parkinson's disease. Clin. Biomech. 18, 197–206.

Marigold, D.S., Eng, J.J., 2006. The relationship of asymmetric weight-bearing with postural sway and visual reliance in stroke. Gait Posture. 23 (2), 249–255.

McCrory, J.L., White, S.C., Lifeso, R.M., 2001. Vertical ground reaction forces: objective measures of gait following hip arthroplasty. Gait Posture 14, 104–109.

Miki, H., Sugano, N., Hagio, K., Nishii, T., Kawakami, H., Kakimoto, A., Nakamura, N., Yoshikawa, H., 2004. Recovery of walking speed and symmetrical movement of the pelvis and lower extremity joints after unilateral THA. J. Biomech. 37, 443–455.

Mourey, F., Grishin, A., d'Athis, P., Pozzo, T., Stapley, P., 2000. Standing up from a chair as a dynamic equilibrium task: a comparison between young and elderly subjects. J. Gerontol. A Biol. Sci. Med. Sci. 55, B425–B431.

Ouellet, D., Moffet, H., 2002. Locomotor deficits before and two months after knee arthroplasty. Arthritis Rheum. 47 (5), 484–493.

Perron, M., Malouin, F., Moffet, H., 2003. Assessing advanced locomotor recovery after total hip arthroplasty with the timed stair test. Clin. Rehabil. 17, 780–786.

Rodriguez, G.M., Aruin, A.S., 2002. The effect of shoe wedges and lifts on symmetry of stance and weight bearing in hemiparetic individuals. Arch. Phys. Med. Rehabil. 83, 478–482.

Roy, G., Nadeau, S., Gravel, D., Malouin, F., McFadyen, B.J., Piotte, F., 2006. The effect of foot position and chair height on the asymmetry of vertical forces during sit-to-stand and stand-to-sit tasks in individuals with hemiparesis. Clin. Biomech. 21, 585–593.

Schwab, F., Lafage, V., Boyce, R., Skalli, W., Farcy, J.P., 2006. Gravity line analysis in adult volunteers: age-related correlation with spinal parameters, pelvic parameters, and foot position. Spine 31 (25), E959–E967.

Shakoor, N., Hurwitz, D.E., Block, J.A., Shott, S., Case, J.P., 2003. Asymmetric knee loading in advanced unilateral hip osteoarthritis. Arthritis Rheum. 48, 1556–1561.

Sicard-Roesnbaum, L., Light, K.E., Behrman, A.L., 2002. Gait, lower extremity strength, and self-assessed mobility after hip arthroplasty. J. Gerontol. A Biol. Sci. Med. Sci. 57, M47–M51.

Sliwinski, M.M., Sisto, S.A., Batavia, M., Chen, B., Forrest, G.F., 2004. Dynamic stability during walking following unilateral total hip arthroplasty. Gait Posture 19, 141–147.

Sonntag, D., Uhlenbrock, D., Bardeleben, A., Kading, M., Hesse, S., 2000. Gait with and without forearm crutches in patients with total hip arthroplasty. Int. J. Rehabil. Res. 23, 233–243.

Su, F.C., Lai, K.A., Hong, W.H., 1998. Rising from chair after total knee arthroplasty. Clin. Biomech. 13, 176–181.

Suter, E., Herzog, W., Leonard, T.R., Nguyen, H., 1998. One-year changes in hind limb kinematics, ground reaction forces and knee stability in an experimental model of osteoarthritis. J. Biomech. 31, 551–557.

Vogt, L., Brettmann, K., Pfeifer, K., Banzer, W., 2003. Walking patterns of hip arthroplasty patients: some observations on the medio-lateral excursions of the trunk. Disabil. Rehabil. 7, 309–317.

Winstein, C.J., Gardner, E.R., McNeal, D.R., Barto, P.S., Nicholson, D.E., 1989. Standing balance training: effect on balance and locomotion in hemiparetic adults. Arch. Phys. Med. Rehabil. 70, 755–762.

Please cite this article in press as: Talis, V.L. et al., Asymmetric leg loading during sit-to-stand, walking and quiet ..., J. Clin. Biomech. (2007), doi:10.1016/j.clinbiomech.2007.11.010