

# Does age affect the response of pelvis and spine to simulated leg length discrepancies? A rasterstereographic pilot study

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## Abstract

**Purpose** The purpose of this study was to investigate age differences in the response of the spine and pelvis to simulated leg length inequalities (LLIs).

**Methods** A total of 107 subjects, separated into three age groups (group 1: 20–39 years, group 2: 40–59 years, group 3: >60 years), were used to evaluate for any age effects in the response to LLIs. LLIs of +10, +20, and +30 mm were simulated with a simulation platform on both sides, and the respective changes of pelvic position (pelvic obliquity, pelvic torsion) and spinal posture (lateral deviation, surface rotation, kyphotic, and lordotic angles) were measured with a rasterstereographic system.

**Results** In all three age groups an increase in LLI led to significant changes in the pelvic position as measured by the parameters of pelvic obliquity and torsion. No significant differences in the response of the pelvis to the LLIs were found between the age groups. In all age groups an increase in surface rotation and lateral deviation of the

spine with increasing LLIs was found. However, none of these parameters responded significantly different between the three age groups.

**Conclusions** Under static conditions, LLIs lead to significant changes of the pelvic position and spinal posture. Despite all known age-related changes, no significant differences of the measured pelvic and spinal parameters in elderly patients as a response to the simulated LLIs occurred.

**Keywords** Leg length inequalities · Spine · Pelvis · Age-dependent · Rasterstereography

## Introduction

Leg length inequalities (LLIs) are found in about 40–70 % of the population [1]. However, the effects of LLIs on gait and posture in different age groups, and, in particular, in older subjects are poorly investigated [2]. LLIs in older patients can be caused, e.g., by actual differences in the length of the osseous structures of the lower extremity, muscle contractures due to neurological deficits, as well as by a loss of cartilage surface due to progressive osteoarthritis [3]. In addition to these structural changes in older patients, fractures of the lower extremity or joint replacement surgeries of the hip or knee joint cause sudden changes in leg length, which can affect gait parameters, lead to changes in motion and alter the kinematic chain of various joints all possibly leading to an imbalanced posture [4]. Because of known age-related changes in the knee, hip joint, and in the spine, it must also be assumed that LLIs have even greater or lesser impact on spinal posture and pelvic position in the elderly. As a consequence, LLIs and pelvic obliquity causing clinical symptoms in the elderly

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**Table 1** Anthropometric data

	Age groups		
	1	2	3
n	42	43	22
Female (%)	55	51	45
Male (%)	45	49	55
Weight (kg) $\pm$ SD	71.6 $\pm$ 11.8	78.6 $\pm$ 16.7	73.8 $\pm$ 10.1
Height (cm) $\pm$ SD	175.4 $\pm$ 7.8	174.1 $\pm$ 9.6	171.8 $\pm$ 7.8
Age (years) $\pm$ SD	23.8 $\pm$ 3	48.9 $\pm$ 5.7	68 $\pm$ 4.7

Subjects in group 1 were between 20 and 39 years, in group 2 between 40 and 59 years and finally in group 3 over 60 years of age

might need different treatment strategies than in younger patients, which has hardly been investigated and discussed before [5].

The quantification and treatment of LLIs and pelvic obliquity still takes place under static conditions, while the patients are standing in front of the physician. This remains challenging, since there do not exist many accurate and reliable methods to quantify these conditions, without having to use isotropic radiation. In previous studies, we have established and evaluated a protocol to quantify and simulate LLIs, and their corresponding effects on spinal posture using a surface topography system and a stand platform [6–8]. The purpose of this present study was to investigate for age differences in the response of the spine and pelvis to simulated LLIs.

## Materials and methods

The human subjects research review board of the University Hospital Duesseldorf, Germany, approved this study. All participants were informed about the study, gave their written consent and were given the option to discontinue participation at any time. A total number of 107 test subjects participated in this study. Proband without any history of lower extremity, pelvic, and spine fracture were included, and subjects with a pre-existing pelvic obliquity  $>15$  mm and a body mass index  $>35$  kg/m<sup>2</sup> were excluded from this study. To be able to evaluate the influence of age on the response to different simulated LLIs, all subjects were grouped into three age groups. In group 1 subjects were between 20 and 39 years, in group 2 between 40 and 59 years, and in group 3 over 60 years of age (Table 1).

The effects of the simulated LLIs on spinal posture and pelvic position were measured with the Formetric<sup>®</sup> rasterstereography system (Diers International GmbH, Schlangenbad, Germany). Rasterstereography, developed in the 1980s by Drerup and Hierholzer, is a method for stereophotogrammetric surface measurements of the back [9].

**Table 2** Spine and pelvic parameters with 0 mm LLI

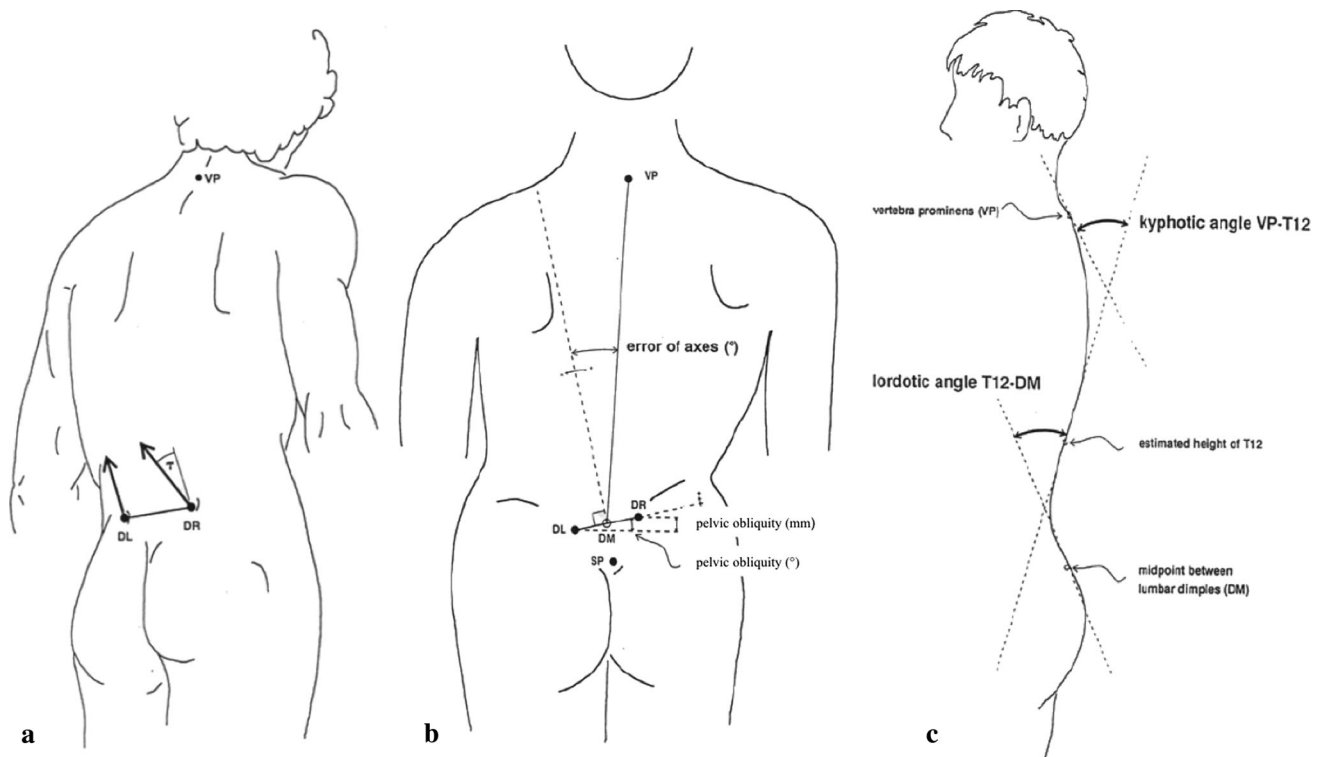
Spinal and pelvic parameters	20–39 years		40–60 years		>60 years	
	Neutral standing					
	Mean	SD	Mean	SD	Mean	SD
Pelvic obliquity (mm)	0.2	4.9	1.2	5	2.2	5.6
Pelvic torsion (°)	0.6	2.5	0.1	2.5	0.5	3.2
Surface rotation (°)	3.1	1.3	3.5	1.7	4.3	2.1
Lateral deviation (mm)	3.9	2.7	4.3	2.4	5.8	3.5
Kyphosis angle (°)	48.2	7.9	51.5	8.5	55.3	9.7
Lordosis angle (°)	37.3	8.6	40.2	9.7	33.8	8.2

The differences of the measured pelvic and spinal parameters in the neutral standing position with 0 mm LLI are shown here

It uses a slide projector to project horizontal parallel light lines onto the unclothed back surface of a patient. A surface reconstruction of the back is performed by transforming the lines and their corresponding curvature into a three-dimensional scatter plot. A 3D-model of the spine can then be calculated based on the specific convex shape of the spinous process of the vertebra prominence and the concavity of the lumbar dimples, which can be automatically localized by the system with an accuracy of  $\pm 1$  mm [10, 11]. The 3D-model was developed by Drerup and Hierholzer and correlated with over 500 reference radiographs of the spine allowing an accurate 3D reconstruction of the subject's spinal column from the topographic image taken [12, 13]. Studies of reproducibility found that intra-rater reliability was high (Chronbach's alpha from 0.921 to 0.992) as was the inter-rater reliability (Chronbach's alpha 0.979) [14, 15] (Table 2).

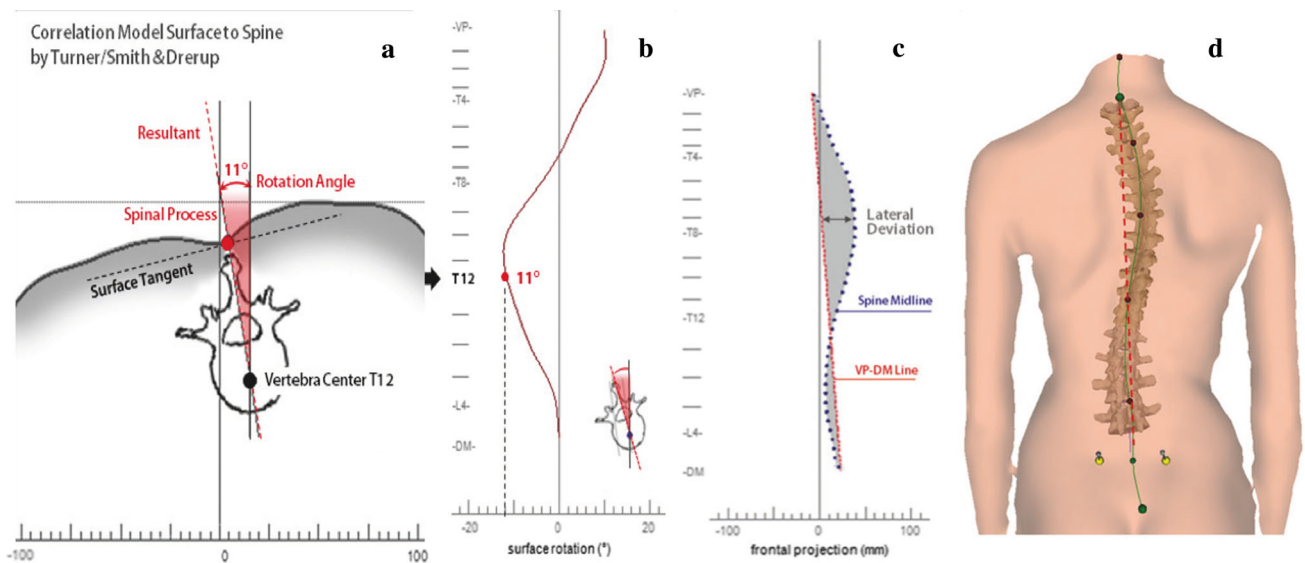
To simulate LLIs, subjects were placed on a stand platform, whose height could be precisely controlled. The weight distribution between both legs was measured by the platform to ensure an equal weight distribution. All subjects stood for 60 s to adapt to the simulated LLI prior to measurement. Two trials of measurements, with each of the respective simulated LLIs, were performed and the mean value of each of these measurements was used for further statistical analysis. During the measurements all subjects stood in a relaxed posture with extended knees on the platform, which is considered the neutral standing position. The following LLIs were simulated: 0 mm (neutral standing position), +10 mm (right leg), +20 mm (right leg), +30 mm (right leg) and –10 mm (left leg), –20 mm (left leg), and –30 mm (left leg).

For the purpose of this study it is necessary to define certain terms regarding the parameters that were measured. The pelvic obliquity is the amount of tilt in millimeter from the horizontal line between the two lumbar dimples DL (left dimple) and DR (right dimple) (Fig. 1). A positive



**Fig. 1** Pelvic torsion (a) is defined as the torsion of the surface normals on the two lumbar dimples (left lumbar dimple (DL) and right lumbar dimple (DR)). Pelvic obliquity (b) is considered as the different height of the two lumbar dimples to each other in °. The kyphotic angle (c) is the angle between the surface tangents on

spinous process of the seventh cervical vertebra (VP) and the calculated spinous process of the 12th thoracic vertebrae (T12). The lordotic angle (d) is defined as the angle between the surface tangents on points T12 and the midpoint between the two lumbar dimples (DM)

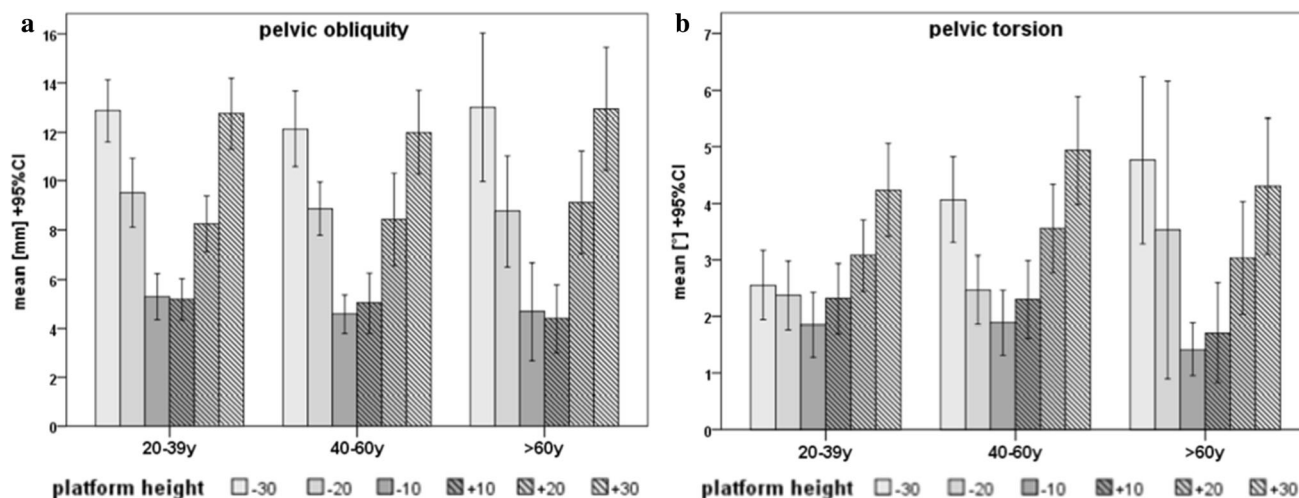


**Fig. 2** The surface rotation (a and b) is the value of the horizontal components of the surface normals on the line of symmetry measured in degrees. The lateral deviation (c and d) is defined as the deviation

of the spinal midline from the line between the VP and DM (midpoint between DL and DR)

value indicates that the right dimple is higher than the left and a negative value indicates that the left dimple is higher than the right. The pelvic torsion measured in degrees is the

rotation of the surface normals of the two lumbar dimples (DL and DR) as shown in Fig. 1. A positive pelvic torsion means that the right hipbone is oriented farther anterior



**Fig. 3** In all three age groups an increase in LLI led to an increase in pelvic obliquity (a) and pelvic torsion (b). Increasing LLIs of 20 mm and more on both sides led to significant changes of the pelvic

obliquity in all groups. For the pelvic torsion no significant changes were found in group 3 with increasing LLIs

than the left hipbone and a negative value signifies that the left hipbone is farther anterior than the right hipbone. Figure 2 illustrates the surface rotation as the value of the horizontal components of the surface normals on the line of symmetry (line connecting the spinous processes of the spine) measured in degrees ( $^{\circ}$ ). The lateral deviation is defined as the deviation of the spinal midline from the line between the VP to midpoint between DL and DR (DM) in the frontal plane (Fig. 2). The kyphotic angle is the angle between the surface tangents on points VP and the calculated spinous process of the 12th thoracic vertebrae (T12) and the lordotic angle is the angle between the surface tangents on points T12 and DM (Fig. 3). All changes in the parameters between the groups were analyzed with respect to the values recorded during neutral standing at 0 mm LLI.

#### Data analysis

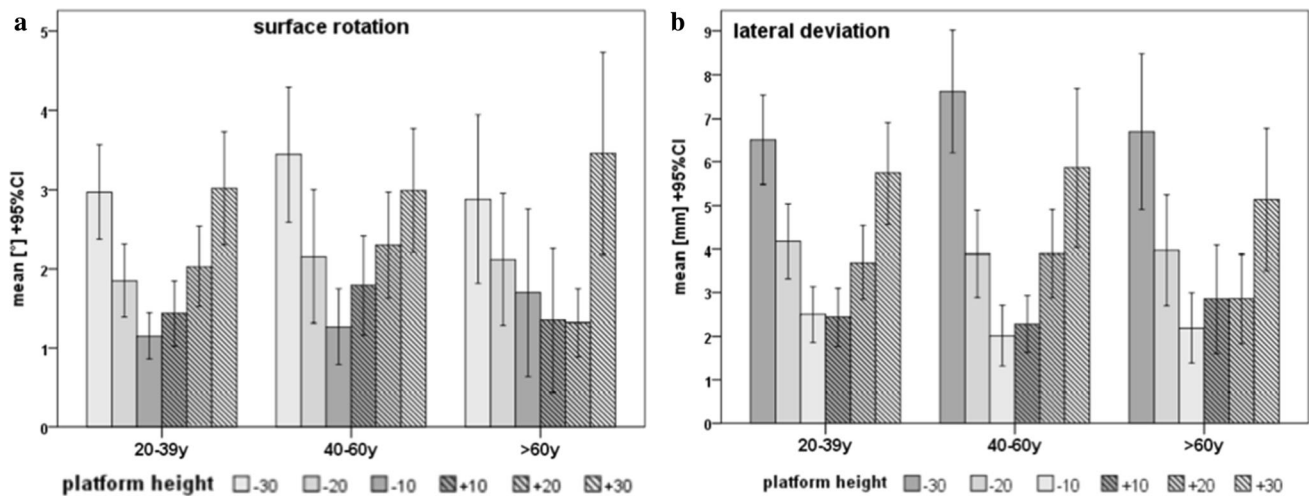
All data were checked for Gaussian distribution by the Chi-square test and presented as mean with standard deviations or 95 % confidence level. Unifactorial ANOVA (modified Bonferroni method) was calculated to check for changes in the values. The level of significance was set at  $p < 0.05$ . Statistical analysis and graphic presentation were prepared using software SPSS 20.0<sup>®</sup> (SPSS Inc., Chicago, USA).

#### Results

In all three age groups an increase in LLI led to an increase in pelvic obliquity (Fig. 3). LLIs of 20 mm and more on both sides led in group 1 and 2 to a significant change

( $p < 0.01$  and  $p < 0.005$ ) of the pelvic obliquity. For group 3 we found significant changes of the pelvic obliquity with a 20-mm LLI on the left ( $p = 0.006$ ) and a 30-mm LLI on the right side ( $p < 0.001$ ). A Bonferroni analysis revealed no significant differences in the response of the pelvic obliquity to the LLIs between the three age groups ( $p = 0.911$  to  $p = 1.0$ ). Figure 3 shows an increase in pelvic torsion with increasing LLIs. In the neutral standing position we did not find significant differences between the three groups for this parameter ( $p = 0.352$ ). An LLI of 30 mm on both sides led to a significant increase in pelvic torsion in group 1 ( $p = 0.006$  and  $p = 0.027$ ). In group 2, a LLI of 20 mm on the right side ( $p = 0.02$ ) and 30 mm ( $p < 0.01$ ) on the left side generated significant changes. In group 3 with the subjects over 60 years of age no statistically significant changes for the pelvic torsion were found ( $p = 1.0$ ). For the parameter pelvic torsion we found significant differences ( $p < 0.001$ ) between the young, middle age, and older age group with LLIs of 30 mm on the left leg side.

Changing the platform stand resulted in an increase in surface rotation (Fig. 4). A significant difference ( $p = 0.024$ ) in the neutral standing position of the surface rotation was found between groups 1 and 3. LLIs of 20 mm and more led to significant changes ( $p = 0.07$  and  $p = 0.037$ ) of the surface rotation in group 1 on both sides. In group 2, LLIs of 30 mm ( $p < 0.001$  and  $p = 0.004$ ) on both sides resulted in significant changes of the surface rotation, whereas in group 3 no significant changes ( $p = 0.716$  to  $p > 1.0$ ) were found in any of the simulated LLIs. We did not find significant changes between the three groups in response to LLIs of the surface rotation ( $p = 0.090$  to  $p = 0.82$ ). The lateral deviation increased



**Fig. 4** In all three age groups an increase in LLI led to an increase in the surface rotation (a). This change was significant with LLIs of 20 or more in groups 1 and 2, whereas in group 3 no significant changes were measured. The lateral deviation of the spine also increased with

increasing LLIs (b). The lateral deviation increased significantly between the neutral standing position and 20 mm and more on the right and 30 mm on the left side in all three groups

significantly between the neutral standing position and 20 mm ( $p < 0.001$ ) and more on the right and 30 mm ( $p < 0.001$ ) on the left side in all three groups (Fig. 4). The Bonferroni analysis revealed no statistically significant differences in the response of the lateral deviation to the LLIs between the age groups ( $p = 0.28$  to  $p = 0.904$ ).

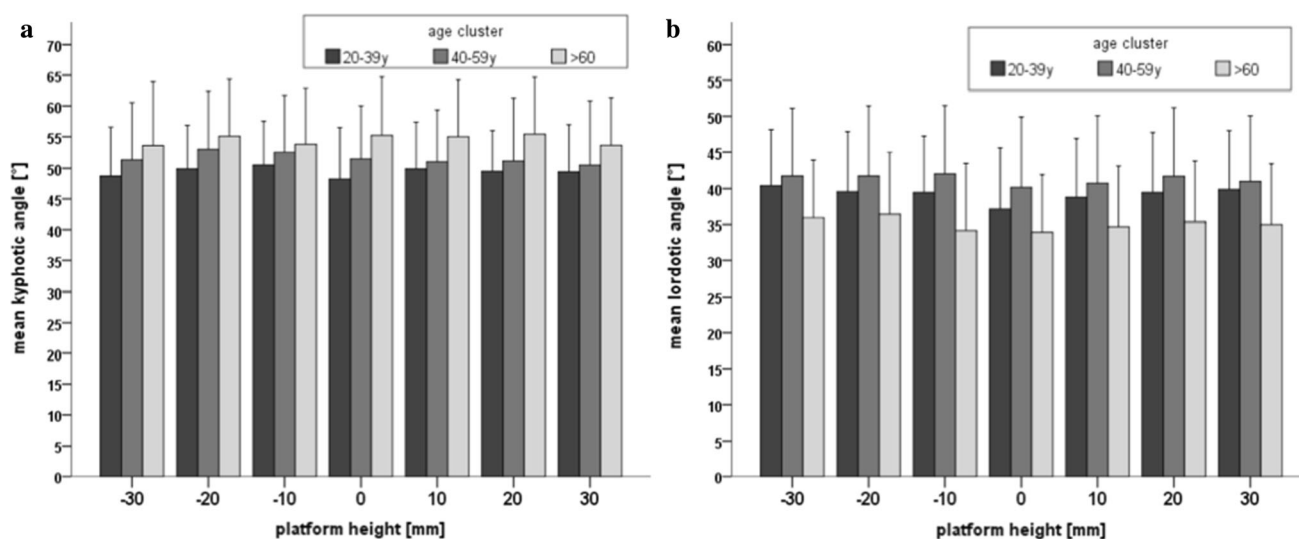
By simulating different LLIs we were not able to create significant changes ( $p = 1.0$ ) of the kyphotic and lordotic angles in all three age groups. With age we did find a significant increase ( $p = 0.007$ ) in the neutral standing position for the kyphotic angle from  $48.2 \pm 7.9^\circ$  in the youngest group to  $55.3 \pm 9.7^\circ$  in the oldest group. For the lordosis angle a significant reduction ( $p = 0.027$ ) was found between groups 2 and 3 in the neutral standing position.

## Discussion

The relationship between ageing and respective musculoskeletal changes such as, e.g., gait alterations are still poorly understood [16]. A recent study found an age-related decline in functional mobility of the elderly, as well as differences in muscle power compared to younger cohorts [17]. Watelain et al. [18] described gait changes in elderly, such as reduced walking velocity, a longer cadence, a shorter step length, and a longer stride time. Chen et al. [19] concluded that such changes could be the result of decreased joint mobility and muscle strength as well as impaired proprioception. Although age-related changes of the musculoskeletal system in elderly exist, no study has yet investigated their influence on the response to leg length discrepancies.

Rasterstereography is a reliable, fast and accurate technique to measure three-dimensionally the spinal posture and pelvic position [14]. Multiple studies have shown the strong test–retest reliability as well as inter- and intra-rater reliability of this technique [20, 21]. Studies by Hackenberg et al. [22] and Goh et al. [23] demonstrated a strong correlation between rasterstereographic measurements and radiographs for the frontal deviation of the spine. Crawford et al. [24] and Goh et al. [25] also showed a high correlation between rasterstereographically and radiologically measured kyphotic and lordotic angles in their studies. In a study by Drerup et al. [26] a strong correlation between the posterior superior iliac spines and the two lumbar dimples was found. Due to this strong correlation, rasterstereography can also be used to determine pelvic parameters such as the pelvic obliquity and pelvic torsion.

An increase in LLI led in groups 1 and 2 to a significant increase of both pelvic parameters. However, in group 3 this increase was only significant for pelvic obliquity and not for pelvic torsion. These results confirm the findings of a study from Young et al. [27], who found a significant increase in pelvic torsion with increasing LLIs. In addition, the results of a previous study from our group showed that LLIs of 20 mm and more lead to significant changes in pelvic obliquity and torsion [8]. However, in this present study, we were not able to detect any differences between the three age groups in the response of the pelvic parameters to the simulated LLIs. In older patients with early stages of hip osteoarthritis, a reduction of hip extension can be associated with kinematic changes at the pelvis [28]. Furthermore, Thurston et al. [28] observed an increase in pelvic obliquity in patients with early stages of coxarthrosis,



**Fig. 5** The simulated LLIs did not create significant changes of the measured sagittal spinal parameters of kyphosis and lordosis. A negative prefix of the LLI means that they are simulated on the left leg side and no prefix that they are simulated on the right side

which was confirmed by the results of our study where we found a trend to increased pelvic obliquity with age. However, the results of our static measurements showed no age-dependent differences in pelvic parameters, but a direct comparison is difficult since most of the current studies have focused on gait changes in older patients rather than on static changes because of leg length discrepancies.

Friberg [29] describes the functional scoliosis caused by LLIs and their respective changes in the spine as predisposing factors to low back pain. Furthermore, Morscher [30] reported that because of the asymmetrical loading forces acting on the spine secondary to scoliosis caused by LLI early degeneration affecting both of the intervertebral disc spaces and the facet joints can occur. In all three age groups an increase in LLI led to an increase in the frontal spinal parameters, indicating that even under static conditions with a short adaptation time to the discrepancies, changes of the spinal posture result from LLIs. In 1991 Irvin [31] found a relationship between the tilt of the sacral base and the degree of resulting scoliosis. These results were confirmed by our study, where an increase in leg length of 20 mm or more resulted in significant changes of the surface rotation and lateral deviation of the spine. Our findings also confirmed the results of Young et al. [27] who found that a lift under one foot led to a lateral deviation with respective vertebral rotation of the spine. Despite, known age-related changes in the elderly, such as reduced muscle tone, loss of elasticity of the intervertebral discs, and osteoarthritis, no differences in the response to LLIs were found between the age groups in the setup of our study.

The different simulated LLIs led to non-significant changes of the kyphosis and lordosis in all three age groups. However, in the neutral standing position, we measured a significant increase in kyphosis and a significant decrease in lordosis with increasing age. These findings are in accordance with Kado et al. [32], who found a 7° increase in kyphosis in older women over a period of 15 years. Hyperkyphosis is a common finding in the elderly especially in women, with a prevalence of up to 40%. In about 36–38% of all cases, an underlying vertebral fracture is the cause for the hyperkyphosis [32]. Hyperkyphosis is also associated with degenerative disc disease, genetic and metabolic disorders and spinal extensor muscle weakness, but in many cases its cause is unknown [32]. Takeda et al. [33] showed in 2009 that anterior disc wedging is a common finding in the lumbar spine of older patients, and that this can lead to a reduction of the lordosis in subjects even without fractures. Legaye et al. [34] suggested that an increase in pelvic anteversion and tilt can result in an increase in lumbar lordosis. Based on their findings we examined the influence of different LLIs and their corresponding pelvic changes on the lordosis and kyphosis. However, our results did not show differences of the sagittal spinal parameters between the three age groups. (Fig. 5)

A limitation of our study is that we examined the immediate and acute effects of simulated LLIs on the spinal posture and pelvic position in three different age groups. In future studies, it would be of great interest to investigate with the same protocol the effects and the compensation for actual long-standing leg length discrepancies under static and dynamic conditions. A further limitation of our study is the relative small sample size in

age group 3 which could lead to a type II error. In addition, we also measured a general population of subjects over the age of 60 years without prior X-ray confirmation of arthritis of the hip joint and the spine, which could be a limitation. Therefore, in future studies patients should be screened and staged for osteoarthritic changes prior to the measurements.

## Conclusion

Under static conditions simulated LLIs led to significant changes of the pelvic position and spinal posture in all tested age groups. However, despite all known age-related changes of the musculoskeletal apparatus, no significant differences in the response to simulated LLIs between the age groups occurred.

**Conflict of interest** None.

## References

1. Woerman AL, Binder-Macleod SA (1984) Leg length discrepancy assessment: accuracy and precision in five clinical methods of evaluation. *J Orthop Sports Phys Ther* 5:230–239 (2107 [pii])
2. Kaufman KR, Miller LS, Sutherland DH (1996) Gait asymmetry in patients with limb-length inequality. *J Pediatr Orthop* 16:144–150
3. Gurney B (2002) Leg length discrepancy. *Gait Posture* 15:195–206
4. Brunet ME, Cook SD, Brinker MR, Dickinson JA (1990) A survey of running injuries in 1505 competitive and recreational runners. *J Sports Med Phys Fit* 30:307–315
5. Blanke DJ, Hageman PA (1989) Comparison of gait of young men and elderly men. *Phys Ther* 69:144–148
6. Betsch M, Rapp W, Przibylla A, Jungbluth P, Hakimi M, Schnependahl J, Thelen S, Wild M (2013) Determination of the amount of leg length inequality that alters spinal posture in healthy subjects using rasterstereography. *Eur Spine J*. doi:10.1007/s00586-013-2720-x
7. Betsch M, Schnependahl J, Dor L, Jungbluth P, Grassmann JP, Windolf J, Thelen S, Hakimi M, Rapp W, Wild M (2011) Influence of foot positions on the spine and pelvis. *Arthritis Care Res (Hoboken)* 63:1758–1765. doi:10.1002/acr.20601
8. Betsch M, Wild M, Grosse B, Rapp W, Horstmann T (2012) The effect of simulating leg length inequality on spinal posture and pelvic position: a dynamic rasterstereographic analysis. *Eur Spine J*. doi:10.1007/s00586-011-1912-5
9. Drerup B, Hierholzer E (1987) Movement of the human pelvis and displacement of related anatomical landmarks on the body surface. *J Biomech* 20:971–977
10. Drerup B, Hierholzer E (1985) Objective determination of anatomical landmarks on the body surface: measurement of the vertebra prominens from surface curvature. *J Biomech* 18:467–474
11. Drerup B, Hierholzer E (1987) Automatic localization of anatomical landmarks on the back surface and construction of a body-fixed coordinate system. *J Biomech* 20:961–970
12. Drerup B, Hierholzer E (1992) Evaluation of frontal radiographs of scoliotic spines—Part II. Relations between lateral deviation, lateral tilt and axial rotation of vertebrae. *J Biomech* 25:1443–1450
13. Drerup B, Hierholzer E (1992) Evaluation of frontal radiographs of scoliotic spines—Part I. Measurement of position and orientation of vertebrae and assessment of clinical shape parameters. *J Biomech* 25:1357–1362
14. Mohokum M, Mendoza S, Udo W, Sitter H, Paletta JR, Skwara A (2010) Reproducibility of rasterstereography for kyphotic and lordotic angles, trunk length, and trunk inclination: a reliability study. *Spine (Phila Pa 1976)* 35:1353–1358. doi:10.1097/BRS.0b013e3181cbc157
15. Schulein S, Mendoza S, Malzkorn R, Harms J, Skwara A (2013) Rasterstereographic evaluation of interobserver and intraobserver reliability in postsurgical adolescent idiopathic scoliosis patients. *J Spinal Disord Tech* 26:E143–E149. doi:10.1097/BSD.0b013e318281608c
16. Lee LW, Zavarei K, Evans J, Lelas JJ, Riley PO, Kerrigan DC (2005) Reduced hip extension in the elderly: dynamic or postural? *Arch Phys Med Rehabil* 86:1851–1854. doi:10.1016/j.apmr.2005.03.008
17. Kerrigan DC, Lee LW, Nieto TJ, Markman JD, Collins JJ, Riley PO (2000) Kinetic alterations independent of walking speed in elderly fallers. *Arch Phys Med Rehabil* 81:730–735
18. Watelain E, Barbier F, Allard P, Thevenon A, Angue JC (2000) Gait pattern classification of healthy elderly men based on biomechanical data. *Arch Phys Med Rehabil* 81:579–586
19. Chen CP, Chen MJ, Pei YC, Lew HL, Wong PY, Tang SF (2003) Sagittal plane loading response during gait in different age groups and in people with knee osteoarthritis. *Am J Phys Med Rehabil* 82:307–312. doi:10.1097/01.PHM.0000056987.33630.56
20. Frerich JM, Hertzler K, Knott P, Mardjetko S (2012) Comparison of radiographic and surface topography measurements in adolescents with idiopathic scoliosis. *Open Orthop J* 6:261–265. doi:10.2174/1874325001206010261
21. Guidetti L, Bonavolonta V, Tito A, Reis VM, Gallotta MC, Baldari C (2013) Intra- and inter-day reliability of spine rasterstereography. *Biomed Res Int* 2013:745480. doi:10.1155/2013/745480
22. Hackenberg L, Hierholzer E (2002) 3-D back surface analysis of severe idiopathic scoliosis by rasterstereography: comparison of rasterstereographic and digitized radiometric data. *Stud Health Technol Inform* 88:86–89
23. Goh S, Price RI, Leedman PJ, Singer KP (2000) A comparison of three methods for measuring thoracic kyphosis: implications for clinical studies. *Rheumatology (Oxford)* 39:310–315
24. Crawford RJ, Price RI, Singer KP (2009) The effect of interspinous implant surgery on back surface shape and radiographic lumbar curvature. *Clin Biomech (Bristol, Avon)* 24:467–472. doi:10.1016/j.clinbiomech.2009.04.003
25. Goh SPR, Leedman PJ, Singer KP (1999) Rasterstereographic analysis of the thoracic sagittal curvature: a reliability study. *J Musculoskel Res* 3:137–142
26. Drerup B, Ellger B, Meyer zu Bentrup FM, Hierholzer E (2001) Functional rasterstereographic images. A new method for biomechanical analysis of skeletal geometry. *Orthopade* 30:242–250
27. Young RS, Andrew PD, Cummings GS (2000) Effect of simulating leg length inequality on pelvic torsion and trunk mobility. *Gait Posture* 11:217–223
28. Thurston AJ (1985) Spinal and pelvic kinematics in osteoarthritis of the hip joint. *Spine (Phila Pa 1976)* 10:467–471
29. Friberg O (1983) Clinical symptoms and biomechanics of lumbar spine and hip joint in leg length inequality. *Spine (Phila Pa 1976)* 8:643–651
30. Morscher E (1977) Etiology and pathophysiology of leg length discrepancies. Springer, Berlin

31. Irvin RE (1991) Reduction of lumbar scoliosis by use of a heel lift to level the sacral base. *J Am Osteopath Assoc* 91(34):37–44
32. Kado DM, Browner WS, Palermo L, Nevitt MC, Genant HK, Cummings SR (1999) Vertebral fractures and mortality in older women: a prospective study. Study of Osteoporotic Fractures Research Group. *Arch Intern Med* 159:1215–1220
33. Takeda N, Kobayashi T, Atsuta Y, Matsuno T, Shirado O, Minami A (2009) Changes in the sagittal spinal alignment of the elderly without vertebral fractures: a minimum 10-year longitudinal study. *J Orthop Sci* 14:748–753. doi:[10.1007/s00776-009-1394-z](https://doi.org/10.1007/s00776-009-1394-z)
34. Legaye J, Duval-Beaupere G, Hecquet J, Marty C (1998) Pelvic incidence: a fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves. *Eur Spine J* 7:99–103