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Effects of repetitive movement on range of motion and stiffness around the neutral orientation of the human lumbar spine

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ABSTRACT

In loading experiments on the lumbar spine, typically three consecutive loading cycles are applied of which the third cycle is used for analysis. The aim of this study was to investigate whether the use of ten instead of three loading cycles reduces effects of viscoelastic behavior in the assessment of range of motion (ROM) and stiffness around the neutral orientation of the human lumbar spine. To this end, twelve cadaveric human lumbar spines (L1–L5) were obtained (mean age: 76.9 years). Before testing, the spines were subjected to a compressive load of 250 N for 1 h. To each spine, ten consecutive loading cycles were applied (-4 Nm to $+4$ Nm) in flexion and extension (*FE*), lateral bending (*LB*) and axial rotation (*AR*). The ROM and stiffness within the neutral zone were calculated per motion segment (L2–L3, L3–L4 or L4–L5) from load–displacement data. It was found that the ROM increased significantly (all $p<0.001$) in all directions after three (*FE*: 0.07 degree/1.0%, *LB*: 0.08 degree/1.5%, and *AR*: 0.04 degree/1.5%) and after ten loading cycles (*FE*: 0.20 degree/2.9%, *LB*: 0.16 degree/3.3%, and *AR*: 0.09 degree/3.3%). Stiffness was not significantly affected, but varied considerably over cycles. Although effects were small, assessment of the tenth cycle instead of the third cycle reduces viscoelastic effects in repeated measurements of ROM, because the spine is closer to a steady state condition, while averaging over loading cycles would improve the assessment of stiffness estimates.

1. Introduction

Spinal segments are subjected to repeated daily movements and loading by gravity and muscle forces (Wilke et al., 1999). Previously it has been shown that mechanical properties of spinal segments are time-dependent, due to its visco- and poro-elastic properties (Koeller et al., 1984; Li et al., 1995; van der Veen et al., 2008; Zilch et al., 1980). Changes in spinal biomechanics are therefore likely to occur when repeated loading cycles are applied. These may affect biological behavior during the day and may act as a confounder in experimental protocols. To our knowledge, little is known about the effects of repetition in biomechanical testing of the human lumbar spine.

Previously, it has been recommended to perform a set of three consecutive loading cycles and to analyze the third cycle in spinal testing (Goel et al., 2006; Wilke et al., 1998b) and most studies have followed this guideline.

The aim of this study was to investigate whether the use of ten instead of three loading cycles would improve preconditioning of the spine and reduce effects of viscoelastic behavior in the assessment of the range of motion (ROM) and stiffness around the neutral orientation of the human lumbar spine.

2. Methods

Twelve lumbar spines (L1–L5) were harvested from freshly frozen (-20 °C) human cadavers (mean age 76.9 years, range 59–90 years). Spines with bridging osteophytes seen on radiographs were excluded. The spines were thawed before testing. Excessive soft tissue and muscle tissue was carefully removed, keeping the anterior and posterior longitudinal ligaments, flavum ligaments, interspinous ligaments and supraspinous ligaments as well as the facet capsular ligaments intact. Specimens were kept hydrated using 0.9% saline-soaked gauzes. After radiographic assessment, spinal segments (L1 and L5) were potted in a casting-mold and partially buried in a low melting point (48 °C) bismuth alloy. All

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articulating parts were kept free. Preparation of specimens was extensively described previously (Bisschop et al., 2011, 2012).

The test setup was described previously (Busscher et al., 2009, 2010). Lumbar spines were placed horizontally in a custom made 4-points bending device in which pure moments in flexion and extension (*FE*), lateral bending (*LB*) and axial rotation (*AR*) can be applied, using a hydraulic materials testing machine (Instron©, model 8872; Instron and IST, Norwood, Canada). Markers containing 3 LED's were screwed to the anterior surface of the vertebral bodies of L2, L3 and L4 and to the L5 casting-mold.

Before testing, a compressive preload of 250 N was applied for 1 h. This axial preload was selected to allow comparison with previous work (Busscher et al., 2009, 2010) and to minimize the risk of buckling of the whole lumbar spine. Mechanical testing started immediately after the preloading period. During testing, no compressive load was applied, again to prevent buckling. Loads were increased to 4 Nm (Busscher et al., 2009, 2010; Guan, 2007; Wilke et al., 1998b) at an angular velocity of 0.5 degrees/s (Wilke et al., 1998a, 1998b). At 4 Nm, loading was decreased, again at 0.5 degrees/s, to reach -4 Nm. Each movement direction was tested for ten consecutive cycles. Force and displacement of the Instron were recorded and digitized at 100 Hz (Instron© Fast Track 2). All tests were performed at room temperature. The first six segments were tested in the order: *FE–LB–AR* while the second six segments were tested in the order: *AR–FE–LB*, to correct for order effects. Time between different loading directions, needed for converting the test setup, was approximately 5 min.

Motions of the LEDs on L2, L3, L4 and the L5 casting-mold were recorded at 100 samples/s by a motion analysis system (Optotrak© 3020, Northern Digital Inc., Waterloo, ON). Using measured forces and LED displacements, a computer program (Mathworks, Natick, MA, USA) calculated the load–displacement curves in the loaded direction for L3 relative to L2, for L4 relative to L3 and for L5 relative to L4, to quantify the behavior of segments L2–L3, L3–L4 and L4–L5.

For each direction (*FE*, *LB* and *AR*) the ROM (degrees) and stiffness (Nm/degree) per motion segment (L2–L3, L3–L4 and L4–L5) were calculated from load–displacement data using Matlab (Mathworks©, Natick, MA, USA). The ROM was calculated between an applied load of -4 Nm and $+4$ Nm. Stiffness was estimated as the slope of a least squares straight line fit through load–displacement data within the neutral zone (Smit et al., 2011). When the r^2-value of this fit was below 0.95, stiffness was calculated between -1.0 Nm and $+1.0$ Nm.

To test the effect of repetitive movements, a repeated measures analysis of variance (ANOVA) was performed with load cycle (using all ten cycles) as a within-subject factor and spinal level as a between-subject factor. In case of significant effects of cycle, we performed planned comparisons (paired *t*-tests) between all subsequent cycles and, additionally, between cycles one and three, cycles three and ten and cycles one and ten. Load sequence effects were tested on the average of ten cycles, using unpaired *t*-tests. The statistical analyses were performed using SPSS for Mac version 20.0 (SPSS Incorporated©, Chicago, IL, USA).

3. Results

ROM and stiffness in all loading directions of L2–L3; specimen 08, L2–L3; specimen 09 and L4–L5; specimen 12, were excluded from analysis due to severely irregular load-displacement curves. Regarding stiffness, linearity of the fit in 16 of the remaining 198 determinations did not reach an r^2-value of >0.95 and for these fits were made on data obtained between $+1$ Nm and -1 Nm Table 1.

ROM in *LB* was affected by load sequence ($p=0.03$), while *FE* ($p=0.27$) and *AR* ($p=0.58$) were not. No significant effects of load sequence on stiffness (*FE*: $p=0.17$; *LB*: $p=0.26$ and *AR*: $p=0.25$) were found.

ROM was significantly affected by cycle in all directions (*FE*: $p<0.001$; *LB*: $p<0.001$ and *FE*: $p<0.001$; Fig. 1, Table 2). No significant effects of segment level or interactions with segment level were found (Table 2). Fig. 1 and Table 3 show a significant increase in ROM between the first and third (*FE*: 0.07 degree/1.0%, *LB*: 0.08 degree/1.5%, and *AR*: 0.04 degree/1.5%), between the third and tenth (*FE*: 0.13 degree/1.9%, *LB*: 0.08 degree/1.8%, and *AR*: 0.05 degree/1.8%) and between the first and tenth load cycle (*FE*: 0.20 degree/2.9%, *LB*: 0.16 degree/3.3%, and *AR*: 0.09 degree/3.3%).

Stiffness was not affected by repetitive movement (Fig. 2, Table 2,) and no significant effects of segment level or interactions with segment level were found (Table 2).

4. Discussion

We studied the effects of repetitive movement in *FE*, *LB* and *AR* on ROM and stiffness in twelve human cadaveric lumbar spines.

Repetitive movement increased ROM significantly after three and ten consecutive loading cycles, while stiffness was unaffected. Therefore, it seems that only ROM, in all three motion directions, is influenced by visco- and/or poroelastic properties of the human lumbar spine. Previously, Wilke et al. (1998a) showed that ambient conditions are of greater influence on ROM than cycle count is. On the other hand, Panjabi et al. (1985) found no differences in ROM after testing his spines for a limited number of cycles in the morning and afternoon over 13 consecutive days with refrigerated storage in between tests. Ambient exposure time in our study was much shorter than in both previous studies.

It has been recommended to use pure moments of 7.5 Nm in testing lumbar spines and about half of that when testing osteoporotic spines (Wilke et al., 1998b). Since we tested spines of elderly donors, which could be osteoporotic, we decided to use a 4 Nm load level. Comparable load levels were previously used (Busscher et al., 2009, 2010; Guan, 2007).

Table 1
Range of motion and stiffness, averaged over spinal levels and per specimen of the first, third and tenth cycle. An average over L2–L3, L3–L4 and L4–L5 was used (*L2–L3 excluded for analysis; **L4–L5 excluded for analysis).

	Range of motion (degrees)									Stiffness (Nm/degree)								
	FE			*LB*			*AR*			*FE*			*LB*			*AR*		
	1st	3rd	10th	1st	3rd	10th	1st	3rd	10th	1st	3rd	10th	1st	3rd	10th	1st	3rd	10th
Specimen 01	9.40	9.51	9.68	7.36	7.56	7.74	5.80	5.87	5.95	0.21	0.19	0.23	0.32	0.28	0.31	0.25	0.22	0.24
Specimen 02	7.89	7.98	8.29	8.37	8.43	8.43	2.89	2.95	3.00	0.23	0.20	0.24	0.33	0.34	0.29	1.21	1.15	1.03
Specimen 03	7.41	7.50	7.74	6.26	6.32	6.49	2.45	2.51	2.57	0.42	0.42	0.41	0.54	0.60	0.40	1.85	1.77	1.83
Specimen 04	6.47	6.39	6.34	7.26	7.25	7.34	1.45	1.43	1.47	0.91	0.99	0.97	0.56	0.65	0.58	2.14	2.73	1.50
Specimen 05	8.08	8.24	8.34	7.41	7.61	7.65	3.73	3.82	3.91	0.38	0.43	0.42	0.72	0.71	0.72	1.46	1.52	1.25
Specimen 06	8.43	8.50	8.68	6.25	6.35	6.51	2.50	2.52	2.55	0.38	0.39	0.39	0.69	0.54	0.55	2.51	2.55	2.43
Specimen 07	3.50	3.55	3.62	4.12	4.13	4.22	1.05	1.06	1.06	1.54	1.53	1.86	1.42	1.69	1.61	7.99	7.91	8.11
Specimen 08	5.08*	5.18*	5.22*	2.52*	2.55*	2.55*	1.17*	1.20*	1.22*	0.65*	0.80*	0.70*	2.47*	2.26*	2.23*	6.40*	5.71*	4.57*
Specimen 09	5.02*	5.03*	5.19*	3.89*	3.94*	3.87*	2.79*	2.85*	2.93*	0.66*	0.58*	0.60*	0.94*	1.06*	0.81*	1.93*	1.82*	1.49*
Specimen 10	8.61	8.63	8.69	6.19	6.29	6.38	4.69	4.74	4.80	0.42	0.38	0.40	0.51	0.46	0.56	0.70	0.75	0.67
Specimen 11	4.65	4.72	4.88	3.00	3.06	3.24	2.46	2.52	2.59	0.85	0.73	0.73	1.52	1.49	1.36	1.69	1.72	1.77
Specimen 12	4.00**	4.13**	4.20**	3.61**	3.66**	3.70**	1.32**	1.32**	1.34**	0.55**	1.06**	0.75**	2.66**	2.52**	3.46**	6.32**	5.20**	6.45**
Average	6.54	6.61	6.74	5.52	5.60	5.68	2.69	2.73	2.78	0.60	0.64	0.64	1.06	1.05	1.07	2.87	2.75	2.61
SD	2.02	2.02	2.06	1.98	2.01	2.03	1.46	1.48	1.50	0.37	0.40	0.44	0.80	0.76	0.96	2.54	2.31	2.46

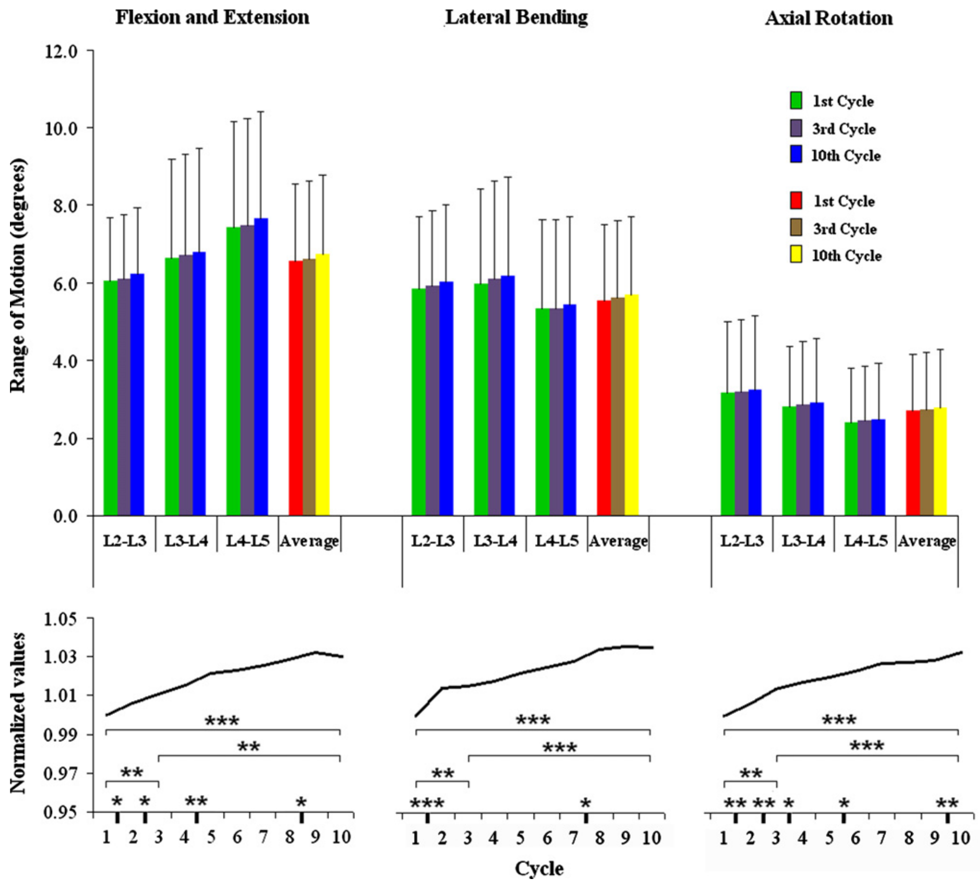

Fig. 1. Effects of repetitive movement on range of motion per spinal segment and also as an average of all spinal segments (mean+SD). In addition, normalized values per cycle, averaging 12 specimens, are presented below. Significant differences between cycles are now shown (*$p<0.05$; **$p<0.01$ and ***$p<0.001$) (Table 3). Note that *p*-values were based on paired *t*-tests including absolute values instead of normalized values.

Table 2
ANOVA outcomes for the range of motion and stiffness, cycles, level and the interaction between cycle and level are shown.

		FE	*LB*	*AR*
ROM (degrees)	**Cycle**	$\boldsymbol{p<0.001}$	$\boldsymbol{p<0.001}$	$\boldsymbol{p<0.001}$
	Level	$p=0.419$	$p=0.719$	$p=0.592$
	Cycle × Level	$p=0.870$	$p=0.265$	$p=0.490$
Stiffness (Nm/degree)	**Cycle**	$p=0.632$	$p=0.545$	$p=0.273$
	Level	$p=0.425$	$p=0.528$	$p=0.405$
	Cycle × Level	$p=0.715$	$p=0.396$	$p=0.691$

Table 3
Follow-up planned comparison showing statistical outcomes of paired *t*-tests between cycles. Percentage differences between the first and third; the third and tenth and the first and tenth cycle were presented with corresponding *p*-values. The use of this technique is justified since there were no significant effects for level or the interaction between level and cycle (Table 2).

ROM	***FE***		***LB***		***AR***	
Cycle	**Δ (%)**	*p*-values	**Δ (%)**	*p*-values	**Δ (%)**	*p*-values
1 versus 3	**+1.0**	$p=0.005$	**+1.5**	$p=0.002$	**+1.5**	$p=0.002$
3 versus 10	**+1.9**	$p=0.001$	**+1.8**	$p<0.001$	**+1.8**	$p<0.001$
1 versus 10	**+2.9**	$p<0.001$	**+3.3**	$p<0.001$	**+3.3**	$p<0.001$

One limitation of this study is that we used a preload of 250 N for 1 h, which is relatively low in perspective of physiological loading (Adams and Dolan, 1995). Preloading with 250 N was chosen, since buckling might occur when loading a complete lumbar spine with a higher load. Another limitation is that we did not apply axial loading during testing, again to prevent buckling. While so-called follower loads would allow for axial loading during bending without buckling, such loads inevitably cause additional moments of unknown magnitude, which would interfere with the purpose of the present study. Furthermore, we did not apply complex 3D motions to the spines, whereas during daily life, the spine is often subjected to a combination of different loading directions. We tested ten repetitive cycles only, but visual inspection (Fig. 1) showed that the effect of repetitive movement for ROM reached a stable phase within ten cycles, while for stiffness, only apparently random variation was observed (Fig. 2). Finally, we only used an angular velocity of 0.5 degrees per second. This velocity is commonly used and fairly low, for this reason we believe that a moderate change of this velocity would not affect our results (Wilke et al., 1998a, 1998b).

ROM showed a small but significant increase between the first and third cycle (0.04–0.08 degrees), but also between the third and tenth cycle (0.05–0.13 degrees). Wilke et al. (1998b) stated that at least two precycles before testing are necessary to minimize viscoelastic effects, because load displacement behavior of the first two cycles could clearly be distinguished, whereas the difference between the second and third cycles was considerably reduced and the third cycle was in many cases nearly identical to all subsequent cycles. We have shown that viscoelastic effects do not stop with three cycles. At ten cycles, ROM curves are closer to an asymptote than at three cycles (Fig. 1). Therefore, in experiments that rely on repeated ROM measurements, preconditioning with ten cycles instead of three would be indicated to reduce confounding effects of viscoelasticity. However, the magnitude of

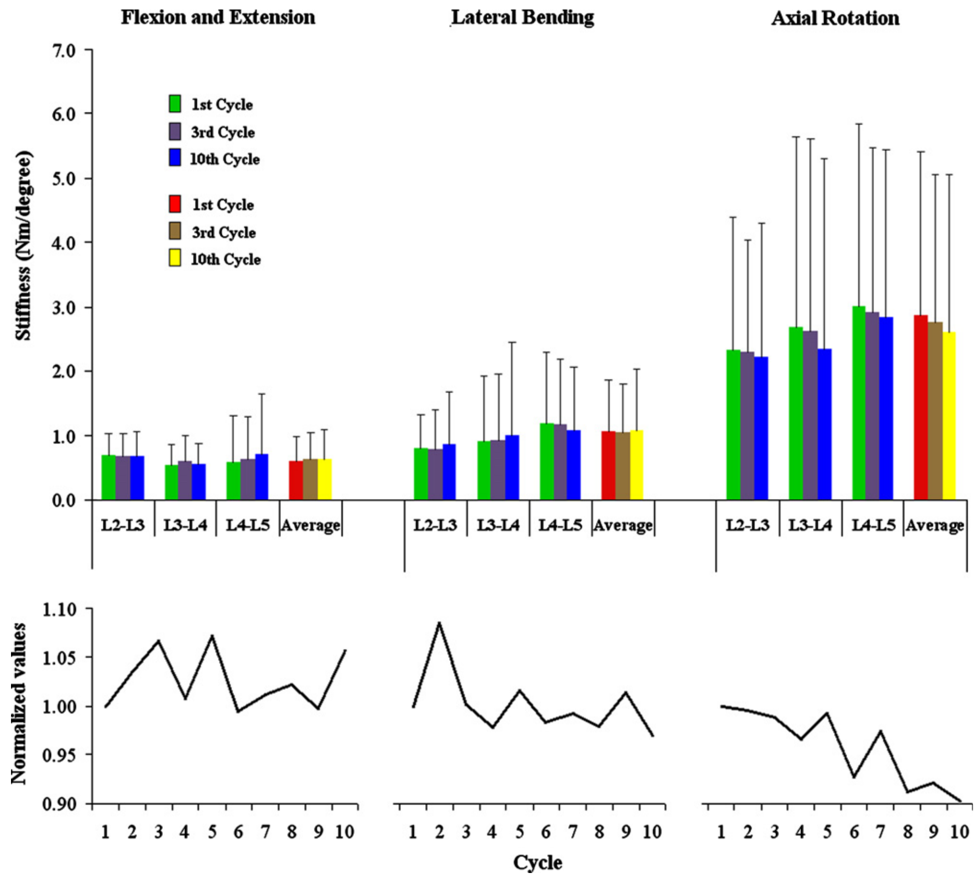

Fig. 2. Effects of repetitive movement on stiffness per spinal segment and also as an average of all spinal segments (mean+SD). In addition, normalized values per cycle, averaging 12 specimens, are presented below. No significant differences between cycles were found.

the viscoelastic effects, both between one and three cycles and between three and ten cycles, is small and it may depend on the specific goal of the experiments whether or not these effects are important.

Fig. 2 shows that spinal stiffness varies considerably. As for ROM, it has also been recommended to analyze the third of three subsequent loading cycles (Goel et al., 2006; Wilke et al., 1998b). Since we did not find clear changes in stiffness over repeated load cycles, our results imply that averaging stiffness values over three cycles, or better over ten cycles, would improve the precision of stiffness estimates.

In conclusion, using ten instead of three cycles reduces viscoelastic effects in repeated measurements, because the spine is closer to a steady state ROM condition. Averaging stiffness values over three, or preferably ten, loading cycles improves the assessment of spinal stiffness.

Conflicts of interest statement

No funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

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