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THREE-DIMENSIONAL MULTI-SEGMENTED SPINE JOINT REACTION FORCES DURING COMMON WORKPLACE PHYSICAL DEMANDS/ACTIVITIES OF DAILY LIVING

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Abstract

Objective: The quantification of inter-segmental spine joint reaction forces during common workplace physical demands.

Background: Many spine reaction force models have focused on the L5/S1 or L4/L5 joints to quantify the vertebral joint reaction forces. However, the L5/S1 or L4/L5 approach neglects most of the intervertebral joints.

Methods: The current study presents a clinically applicable and noninvasive model which calculates the spinal joint reaction forces at six different regions of the spine. Subjects completed four ambulatory activities of daily living: level walking, obstacle crossing, stair ascent, and stair descent.

Results: Peak joint spinal reaction forces were compared between tasks and spine regions. Differences existed in the bodyweight normalized vertical joint reaction forces where the walking (8.05±3.19N/kg) task had significantly smaller peak reaction forces than the stair descent (12.12±1.32N/kg) agreeing with lower extremity data comparing walking and stair descent tasks.

Conclusion: This method appears to be effective in estimating the joint reaction forces using a segmental spine model. The results suggesting the main effect of peak reactions forces in the segmental spine can be influenced by task.

Keywords

Biomechanical models; Spine; Gait; Kinetics; Spine; Biomechanics

INTRODUCTION

Physical demands or activities of daily living (ADL) are actions performed by the human body at the workplace (physical demands) or to proceed through life (ADL's).[1,2] Movement or change in position will cause an increase in spinal loading[3] which has been shown to increase injury potential in the back.[4] Many studies have examined the spinal load while

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walking on level surfaces,[5–9] ascending and descending stairs[10] and have focused on the lower back such as the L4/L5 or L5/S1 joint[11,12] and even in special populations as amputees.[13] What is not known is how the spine loads act as they propagate up the chain away from the low back.

Traditionally, the quantitative methods used to describe the motions model the trunk as one rigid segment[14,15] — this in turn limits the resolution by which spine joint reaction forces can be estimated — which is usually one joint in the low back. Recently, the resolution by which the trunk motions are modeled has increased from one segment[9,10,16] to multiple segments.[7,8,17,18] By using the motions from a high resolution kinematic model, joint reaction forces can be estimated at each of the adjacent joints between two rigid bodies as even minor movements of the trunk center of mass (COM) can substantially impact joint reaction loads and demands on the muscles throughout the body.[19]

Spinal joint reaction forces have been directly measured using a hypodermic needle inserted between vertebral bodies[20,21] implanted with telemetered spinal fixators[22] and with animal models[15,23] Though direct measurements of intervertebral discs appear to be most advantageous in providing a complete understanding of the pressures and forces associated with motions in the spine, there are inherent problems such as irregular pressure distribution and alternate load paths including posterior elements. Additionally, these procedures are very invasive and would be difficult to apply to a large clinical population.

Inverse dynamic methods which use a rigid body-linked segment models are popular methods used to develop a comprehension to the overall muscle activity and forces at each joint in order to understand the cause of body movement.[16,24–26] The outcomes from this procedure represent the sum of all forces and moments acting on the joint and require measured force to interact with the foot — commonly by a force plate. This method has been used numerous times in healthy individuals to estimate joint forces during walking,[5,12,16,27] running,[28–33] obstacle crossing,[32,34–42] lifting[14,43–47] and stair negotiation[48–58] as well as pathologic populations.[59–62] In spite of some limitations of linked segment models[63] and precise criticisms for the application of bottom-up approaches to locomotion,[5] the linked segment approach has been comprehensively validated for estimating forces and net joint moments acting at the low back during a variety of tasks.[5,25,64] The inherent advantages of using an inverse dynamic approach to estimate the joint reaction forces in the trunk do outweigh any limitations or concerns regarding this method.

It is therefore logical to use the kinematics from higher resolution trunk models and estimate the joint reaction forces using an inverse dynamic-linked rigid body approach. This allows for practicality in applying the method to a high number of populations and can easily be incorporated into typical full-body-surface maker sets. The purpose of this study is to explore the feasibility of an *in vivo* multi-segment spine marker set used to estimate the joint reaction forces at various spinal joints during different physical demands/ADL in young adults. It is hypothesized that unique ambulatory activities will affect joint reaction forces at specific joints of the spine. Specifically, it is thought that obstacle crossing and stair ascent will have larger joint reaction forces than walking due to the increased force needed to negotiate the obstacle or increase force related to elevation of the stairs. Additionally, it is hypothesized that stair descent will involve less joint reaction force than walking, as gravity will assist walking tasks in the decrease in elevation.

METHODS AND MATERIALS

Subjects

About 14 healthy young adults (7 males/7 females; mean age: 27.9±5.9 years, mean height 176.0±27.7 cm, mean mass 67.8±17.2 kg), were recruited to participate in the study. Subjects did not have a history or clinical evidence of neurological, musculoskeletal or other medical conditions affecting gait performance, such as stroke, head trauma, neurological disease (i.e. Parkinson's, diabetic neuropathy), visual impairment uncorrectable by lenses and dementia. This research complied with tenets of the Declaration of Helsinki and was approved by the Institutional Review Board at the University of Oregon. Informed consent was obtained from each participant.

Experimental Setup

Whole-body motion data were collected with a 10 Eagle camera motion analysis system using Cortex software (Motion Analysis Corporation, Santa Rosa, CA) and 62 retro-reflective markers (diameter = 14mm) were placed on the subject. In addition to a whole-body marker set,[39] 22 markers were placed on the subject's back as described by Breloff and Chou.[17] Three-dimensional marker position data were collected at 60 Hz and low-pass filtered using a fourth-order Butterworth filter with the cutoff frequency set at 5 Hz.

Two force plate configurations were used in the current study — one for nonstair and one for the stair tasks. For the nonstair related tasks, walking and obstacle crossing, force plate configuration consisted of three force plates (Advanced Mechanical Technologies, Inc., Watertown, MA) placed in series and embedded level into the laboratory floor. The first two force plates were immediately adjacent to one another, and the third plate was separated by a distance of 15 cm.[39,65] This setup was to accommodate subjects walking with different step lengths [Figs. 1(A) and 1(B)]. Stair-related tasks utilized four force plates to record ground reaction force data. Two force plates were embedded level into the laboratory floor and two implanted into a staircase. The staircase — which included three steps [Figs. 1(C) and 1(D)]. — had a rise of 17.8 cm, a run of 30.5 cm and a width of 80 cm, forming a stair angle (rise/run) of 30°.[52,66]

Gait events for all tasks, heel strike (HS) and toe off (TO), were determined using the vertical ground reaction force (GRFv). HS occurred when the GRFv was greater than 10% of the maximum GRFv, and TO was occurred when the GRFv was less than 10% of the maximum GRFv.[67–69]

Experimental Protocol

Subjects were asked to wear spandex shorts with no shirt for men and a dance leotard with open back for women and performed four different randomly assigned tasks while barefoot: level ground walking, obstacle crossing, stair ascent, and stair descent as shown in Figs. 1 and 2. The level walking task required subjects to walk along a **10-m** walkway [Fig. 1(A)].

With the obstacle crossing task, subjects were asked to initiate walking from a distance which allowed at least three steps prior to encountering the obstacle, step over the obstacle, and continue walking. The obstacle was set at 10% of body height and made of a polyvinyl chloride (PVC) pipe measuring 1.5 m and a diameter of 2.5 cm, which was presented to the subjects prior to obstacle crossing trials, as in Fig. 1(B).[39] During the stair ascent, subjects were asked to approach the stairs while walking on level ground, climb the stairs, and continue walking to the end of the elevated walkway as in Fig. 1(C).[52,66] The starting position for each subject was adjusted to allow at least three steps before stepping onto the first stair. Subjects initiated their stair descent trials from the back end of the elevated walkway, descended the stairs, and continued walking for several steps as in Fig. 1(D).[52,66]

Kinematic Analysis

Five activity cycles were analyzed for each condition. Level ground walking activity was defined as the time interval between two consecutive ipsilateral HSs [FP 3 to FP 1; Fig. 1(A)]. The obstacle crossing stride was defined as the HS of the leading limb before the obstacle to the HS of the same limb after clearing the obstacle [FP 3 to FP 1; Fig. 1(B)]. Stair ascent cycle was the duration between consecutive ipsilateral HSs of last level ground contact and the second stair [FP 2 to FP 4; Fig. 1(C)], and stair descent examined consecutive ipsilateral HSs following first step down toward ground [FP 4 to FP 2; Fig. 1(D)].

A MATLAB® (Mathworks, Natick, MA) program was developed to calculate six adjacent segmental spinal forces.[17] The joints in the current study are sacrum-to-lower lumbar, lower lumbar-to-upper lumbar, upper lumbar-to-lower thoracic, lower thoracic-to-lower middle thoracic, lower middle thoracic-to-upper middle thoracic and upper middle thoracic-to-upper thoracic (Fig. 2).

Kinetic Analysis

Segmented spine joint reaction forces were calculated using a linked rigid body inverse dynamic algorithm starting with the lower extremities. The pelvis was modeled as a rigid body and lower extremity forces were transferred to the spine through the hip joints and pelvic segment, which includes the femur heads, where hip joint reaction forces are well documented.[63,70] This character was paramount for the single segment definition of the pelvis [Fig. 3(A)]. COM location of the pelvis was the midpoint between the lines joining the left and right anterior superior iliac spine and the left and right posterior superior iliac spine [Fig. 3(A)]. The mass of the pelvis COM was calculated using regression equations.[71] The pelvis COM segmental acceleration was calculated using the procedure described by Winter.[63] The hip reaction forces, pelvis segmental mass and pelvis segmental acceleration were summed to provide the reaction force at the first sacral joint as shown in Eqs. (1) and (2).[63]

Vector form equation for reaction force at sacral joint is given by

$$\mathbf{jrf}_{\mathbf{S1}} = m\mathbf{a}_{\text{pelvisCOM}} - m\mathbf{g}_{\text{pelvis}} - \mathbf{f}_{\text{r.hip}} - \mathbf{f}_{\text{l.hip}}. \quad (1)$$

Vector form equation for reaction force at subsequent spine segments is given by

$$\mathbf{jrf}_{\text{proximal spine segment}} = m\mathbf{a}_{\text{pelvisCOM}} - m\mathbf{g}_{\text{pelvis}} - \mathbf{f}_{\text{distal spine segment}}. \quad (2)$$

Segmental accelerations were determined at the COM of each spine segment using the procedure outlined by Winter *et al.*[63] The mass of each spinal segment was calculated by first modeling the trunk segment as homogeneous rigid bodies. Then, several virtual markers were added in front of the trunk and estimated by eight solid ellipsoids. The trunk shape was described by 1027 tetrahedrons defined by the surface and virtual markers [Fig. 3(B)]. The volume of each ellipsoid was then calculated using both actual and virtual markers. The density of the human body was represented by 1.063 kg/cm^3.[72] The density of the human body was then multiplied by the volume of each segment to determine the mass.

Validation

To validate the current procedure for spine joint reaction force calculation, lower extremity joint reaction forces were compared between the current method and previously validated.[73,74] third party software (Othrotrac software, Motion Analysis Corporation, Santa Rosa, CA). Lower extremity comparisons were necessary as Othrotrac only calculates lower extremity (ankle, knee and hip dynamics) — thus the need for the MATLAB code to calculate spine reaction forces. To validate the two different approaches, the similarity in the waveforms was compared using the coefficient of multiple correlations (CMC).[16,75] The two calculation methods (MATLAB & Orthotrac (OT)) produced similar wave forms in the lower extremity, which were then evaluated using the CMC procedure.[16,75] Data were found to have strong correlations (>0.90) in all planes of motion. These results suggested that the inverse dynamic calculation procedures between MATLAB and OT were similar.[16,75] Therefore, the results observed from the segmented spine can be considered reasonable based on the inverse dynamic procedure and the assumptions that accompany that procedure.[24,25,43,44,63] Selected vertical reaction forces are shown in Fig. 4(A), though all directions had similar comparisons between the two methods.

Joint reaction forces have similar shape from distal to proximal with smaller magnitudes.[63] To ensure that this character was present in the segmented spine, static trial reaction forces were calculated at each spine segment. The results were exactly as expected with the most distal segment (Sacrum to Lower Lumbar) displaying the largest magnitude with each proximal segment yielding slightly less joint reaction force [Fig. 4(B)].

Data Analysis

The estimated peak spine reaction force (normalized by body mass) in each plane was analyzed using a two-way within factor analysis of variance (ANOVA) to determine if differences in the peak spine reaction force changed due to task and spine joint. Post hoc *t*-tests were performed on data with significant interaction and main effects. Data analysis was completed in SPSS 23 and all significant values were sent to $p < 0.05$.

RESULTS

Spine joint reaction forces were not significantly different between joint regions and task only influenced the spine joint reaction forces in the vertical direction. The reaction force from the six spine joints had similar waveforms, therefore, the reaction forces for one joint from each task is shown (Fig. 5). Data were visually illustrated in a nonnormalized manner; however, only normalized data were analyzed. The results comparing different spine joint reaction forces and task types are summarized in Table 1 and Fig. 6.

Anterior–Posterior Segmental Force Peaks

No interaction was found between task and spine region for the anterior–posterior segmental force peaks ($p = 0.429$). Main effects for task ($p = 0.628$) and spine region ($p = 0.952$) were not significant (Fig. 6, Table 1).

Medial–Lateral Segmental Force Peaks

No interaction was found for the peak segmental forces in the medial–lateral direction ($p = 0.999$). The main effects for both task ($p = 0.536$) and spine region ($p = 0.772$) in relation to the medial–lateral force peaks were not significant (Fig. 6, Table 1).

Vertical Segmental Force Peaks

No interaction for vertical segmental force peaks of task and spine region was found ($p = 0{:}842$). There was a significant ($p < 0{:}001$) main effect for task (Table 1). Post hoc pairwise comparisons of the task marginal means showed that the walking (8.05±3.19 N/kg) task had significantly smaller peak reaction forces than the stair descent (12.12±1.32 N/kg) task ($p = 0{:}007$). It should be noted that the obstacle crossing (9.43±0.76 N/kg) task was trending to have significantly larger reaction forces than walking ($p = 0.09$). The spine region main effect ($p = 0.392$) was insignificant (Fig. 6).

DISCUSSION

This study compared multi-segmented peak spine joint reaction forces during four distinct ambulatory ADL/workplace physical demands (level walking, obstacle crossing, stair ascent and stair descent) using trunk motions from a multi-segmented trunk model and applying an inverse dynamic approach. Contrary to the hypothesis, only the peak vertical reaction force changed due to different tasks and there were no differences in peak joint reaction forces between the different joints.

Multi-segmented trunk kinematics differ between joints[17] and when different tasks are introduced[18] — leading to the speculation that this may lead to different joint forces. As this was not entirely the case, the possible explanation are the tasks which used in the current study were primarily gait tasks (walking, obstacle crossing, stair ascent and descent) and which require the subjects to remain mostly vertical, and not have much intra-trunk movement. With the lack of overall intra-trunk movement, the accelerations by the individual spine segments would be similar. Therefore, the difference in joint reaction forces between segments with similar mass and comparable accelerations will generally not be statistically significant.

The introduction of task was able to elicit a change in spine joint reaction forces in the vertical direction between walking and stair descent. This is in agreement with the lower extremity where stair descent has higher moments than walking[48,56,58] and the ground reaction forces change dramatically from level walking to stair descent.[76] Furthermore, though it is a different measurement method, spinal fixators in two patients did show stair descent to have a slightly larger force than walking, however, this proved to be statistically insignificant.[22] Of note, the anterior–posterior joint reaction forces were smaller during the stair descent task than the walking task. Though they are not significantly different, these data patterns agree with the lower extremity.[58] All these had the purpose of indicating, though these are not fully conclusive in the current study, that different tasks and joint regions can potentially have different forces depending on the perturbations.

All tasks were completed at the subjects' own comfortable pace, which generally indicates an average walking speed of approximately 1.50 m/s for young adults.[77] It has been shown a slow jog, or speeds greater than 2.0 m/s are required before changes in GRFVs are observed.[30] Thus the self-selected speeds of the individuals in this study might not have induced changes in the ground reaction force which in turn would have induced a change in the peak spine joint reaction forces. Therefore, future studies could be conducted while using varying speeds to determine if there is an observable difference in spinal joint reaction forces as speed increases. This has application in daily life and work place application; however, results from a speed study would have a much larger sports application.

Limitations

Electromyography (EMG) is commonly used in gait analysis to quantify muscle activation patterns.[48,56,78] In the current study, EMG was not used because the erector spinae (spinalis, longissimus & illiocostalis) are the only surface muscle groups encompassing the trunk segments and the information garnered would not be as helpful as the rectus femoris in studies of the lower extremity. Additionally, the spine joint reaction force is comprised of force contact between the intervertebral discs and vertebral bodies and all the muscle forces around the spine and EMG are not needed in the chosen calculation procedure. Moreover, considering gait speed could have a major influence on the joint reaction force and the future studies might consider controlling gait speed between subjects and ADL.

Future Studies

This study examined spinal joint reaction forces — future studies should also examine multi-segmented moments. For example, significant differences in lower extremity moments have been reported during stair climbing when compared to walking.[48,58,79] Additionally, joint moments at the L4/L5 level have found consistent patterns and different peak moments as walking speed increased.[5] This may suggest that observing segmental spine motion could find that various spine regions produce multiple moments in response to different tasks. Though there is no direct application of this study, it is suggested that this could be investigated in the future.

CONCLUSION

A multi-segmented spine model appears to be effective in estimating the joint reaction forces using a segmental spine model. Though the hypothesis was not fully supported, the results found that the main effect of peak reaction forces in the segmental spine can be influenced by task. However, further testing is necessary with the inclusion of a larger and more diverse sample set and should include testing with multiple speeds. One future direction for application of this model would be to investigate sport applications which involve more intra-trunk motion than walking-based tasks.

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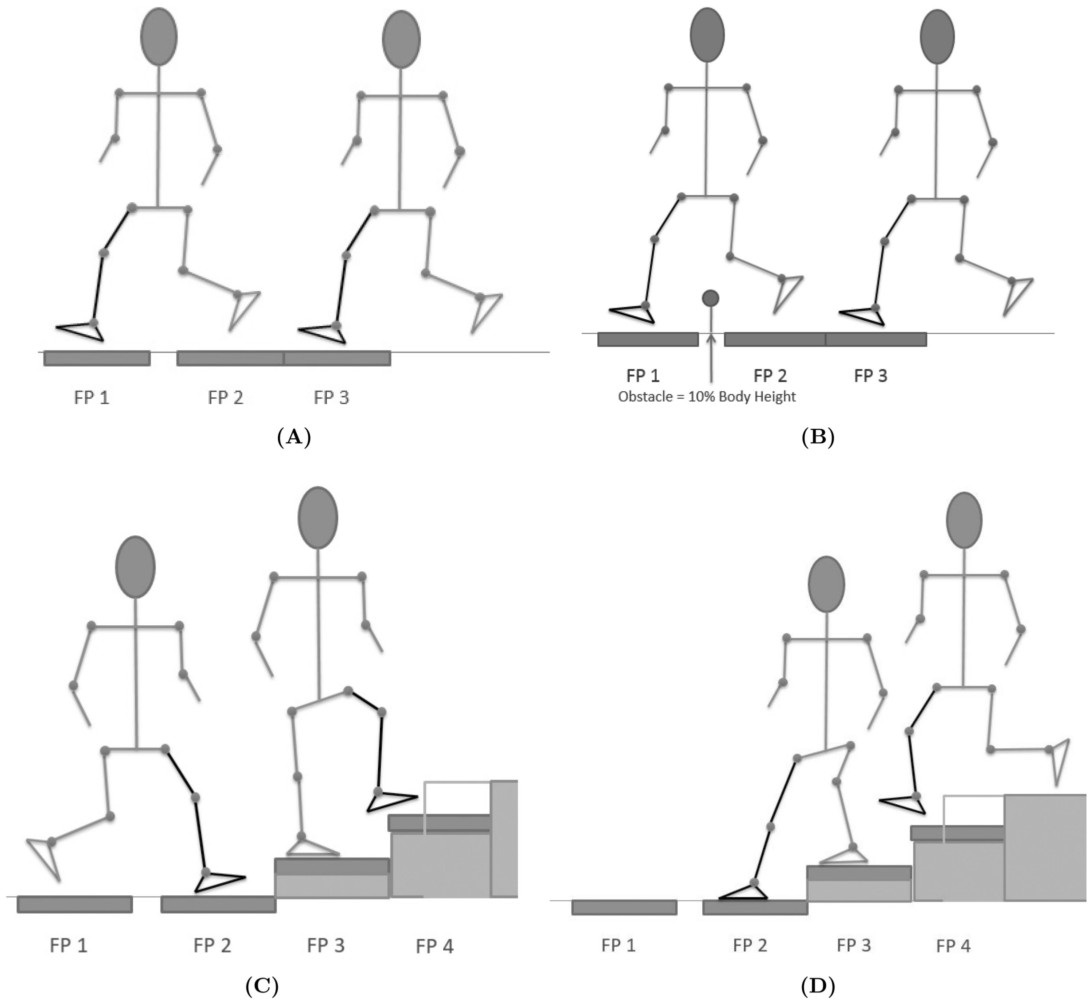


Fig. 1.

Definition of each task. (**A**) Level walking (*W*) — ipsilateral HSs, (**B**) Obstacle Crossing (OC) — Leading limb ipsilateral HSs, (**C**) Stair Ascent (SA) — ipsilateral HSs, (**D**) Stair Descent (SD)-ipsilateral HSs.

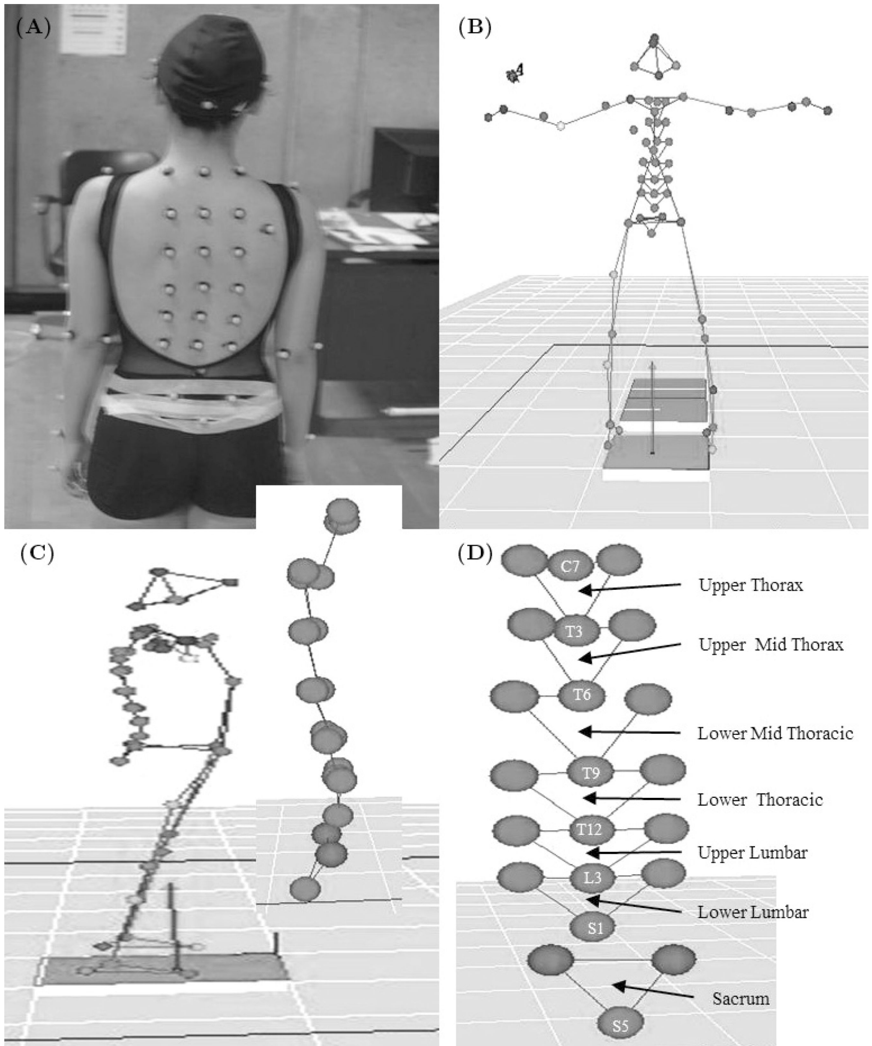
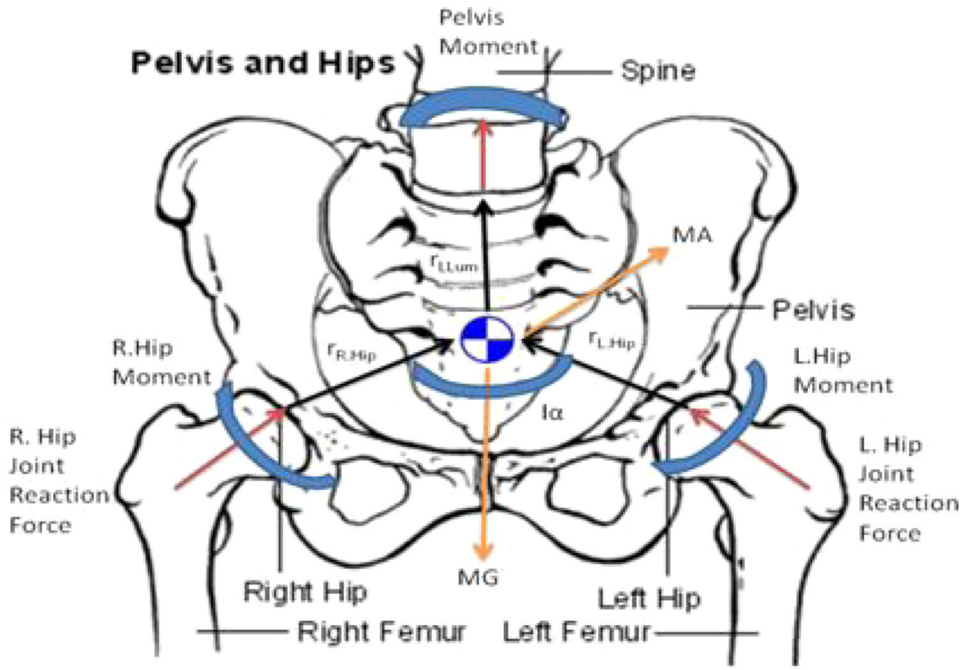
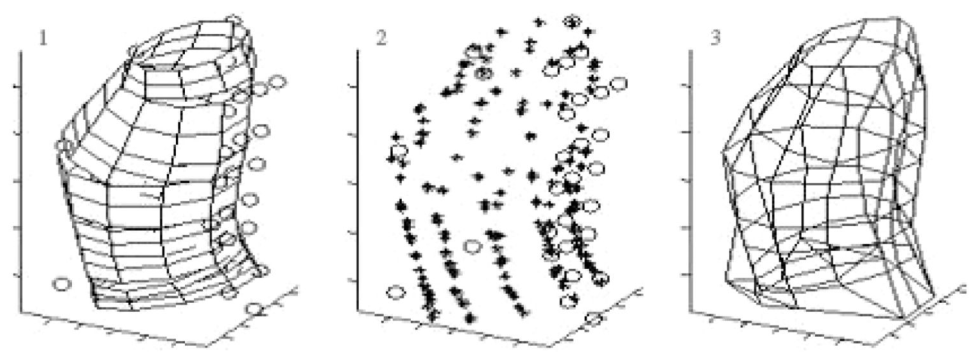


Fig. 2.

Segmental spine maker set with adjacent segments — sacrum-to-lower lumbar, lower lumbar-to-upper lumbar, upper lumbar-to-lower thoracic, lower thoracic-to-lower middle thoracic, lower middle thoracic-to-upper middle thoracic and upper middle thoracic-to-upper thoracic — which joint reaction forces were calculated.



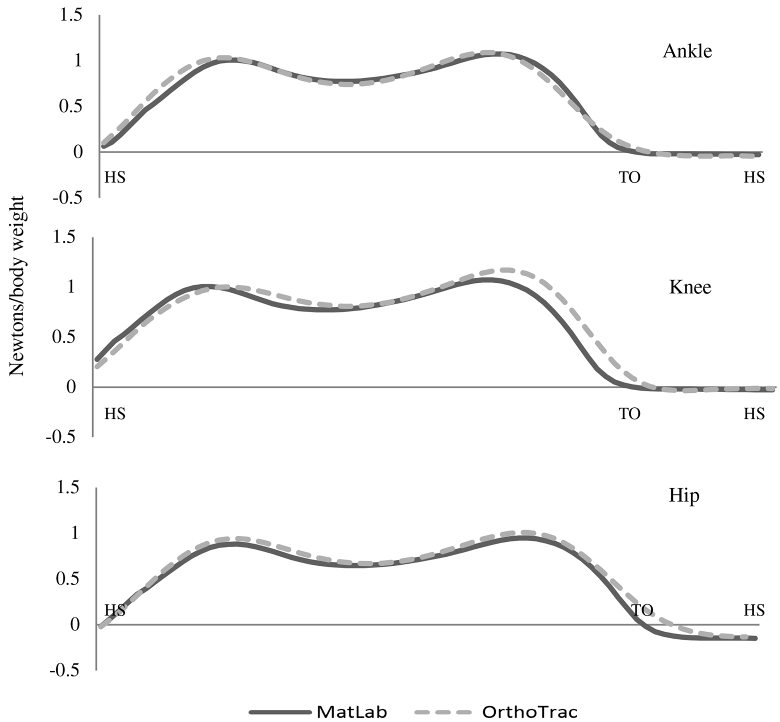
(**A**)



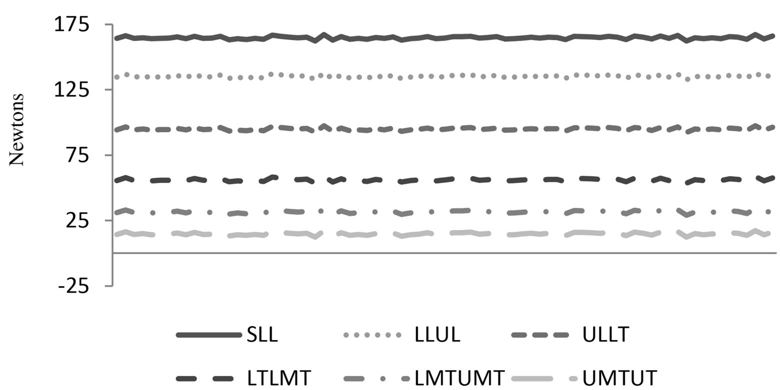
(**B**)

Fig. 3.

(**A**) Free body diagram of the pelvis. Showing how lower extremity forces will be handled to continue the summation of forces into the spine. (**B1**) Eight ellipsoids indicated by the attached markers (circles). (**B2**) Virtual markers (asterisks) estimated by the ellipsoids. (**B3**) The trunk shape described by tetrahedrons.



(A)



(B)

Fig. 4.

Validation Data. (**A**) Ensemble average lower extremity vertical joint reaction forces as calculated by OT and MATLAB — Ankle, Knee and Hip. (**B**) Static joint reaction forces at each spine region.

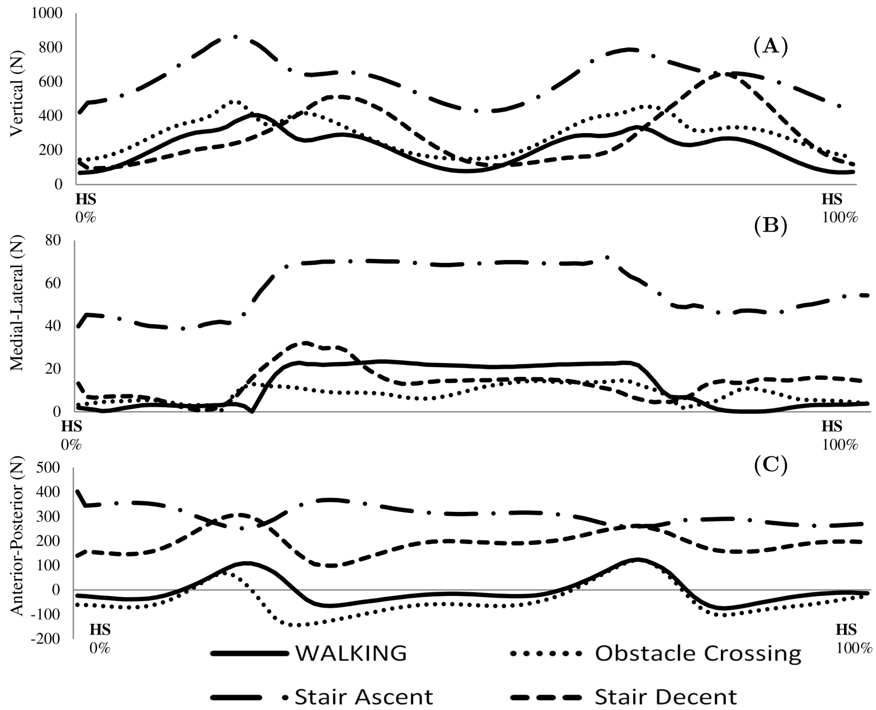
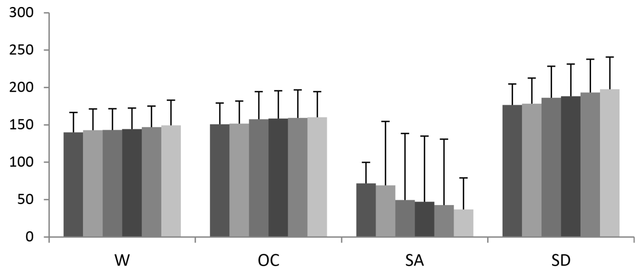
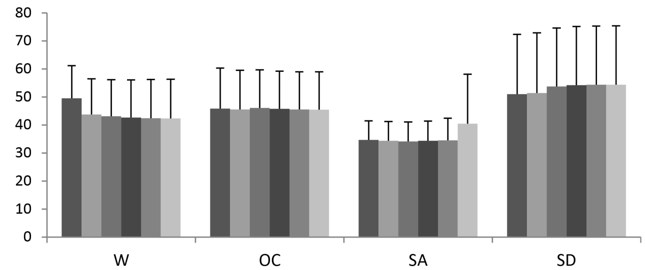


Fig. 5.

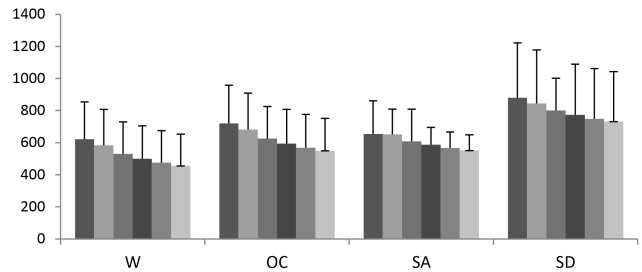
Lower thoracic-to-lower middle thoracic (LTLMT) ensemble average segmented spinal joint reaction forces for each plan of motion during each of the four ambulatory tasks of daily living. Visual inspection found all spine regions to have similar patterns, thus the LTLMT was chosen as a representative sample.



(A)



(B)



(C)

Fig. 6.

Nonnormalized spine joint reaction forces for spine region and multiple tasks. (A) Anterior–Posterior, (B) Medial–Lateral, and (C) Vertical.

Notes: ■ Sacrum-to-Lower Lumbar, ■Lower Lumbar-to-Upper Lumbar, ■Upper Lumbar-to-Lower Thoracic, ■Lower Thoracic-to-Lower Middle Thoracic, ■Lower Middle Thoracic-to-Upper Middle Thoracic, and ■Upper Middle Thoracic-to-Upper Thoracic. W = walking, OC = obstacle crossing, SA = stair assent, and SD = stair descent.

Table 1.

Nonnormalized Maximum Peak Segmental Joint Reaction Forces in the Anterior/Posterior, Medial/Lateral and Vertical Directions for Each ADL.

	Walking	Obstacle Crossing	Stair Ascent	Stair Descent	*p*-Value (Main Effect) Normalized
Maximum anterior/posterior joint reaction force (*N*), Mean (Stdv)					
Task (overall)					0.628
Spine level (overall)					0.952
SLL	139.88 ± 26.71	150.74 ± 30.05	71.61 ± 85.70	176.61 ± 33.75	
LLUL	142.72 ± 28.41	151.64 ± 30.16	69.13 ± 85.41	178.43 ± 34.16	
ULLT	143.29 ± 28.13	157.36 ± 37.07	49.48 ± 88.86	186.16 ± 42.22	
LTLMT	144.21 ± 28.18	158.31 ± 37.27	135.21 ± 243.21	188.29 ± 43.00	
LMTUMT	147.05 ± 28.01	159.27 ± 37.40	42.75 ± 88.16	193.15 ± 44.64	
UMTUT	149.31 ± 28.55	160.22 ± 37.74	36.82 ± 87.46	197.78 ± 46.72	
Maximum medial/lateral joint reaction force (*N*) Mean (Stdv)					
Task (overall)					0.536
Spine level (overall)					0.772
SLL	49.49 ± 11.69	45.86 ± 14.46	34.62 ± 6.82	51.00 ± 21.35	
LLUL	43.75 ± 12.71	45.51 ± 14.00	34.38 ± 6.84	51.39 ± 21.48	
ULLT	43.13 ± 13.02	46.09 ± 13.58	34.08 ± 6.98	53.75 ± 20.83	
LTLMT	42.60 ± 13.48	45.71 ± 13.45	34.36 ± 7.04	54.20 ± 20.97	
LMTUMT	42.41 ± 13.80	45.52 ± 13.47	34.51 ± 7.89	54.33 ± 20.99	
UMTUT	42.34 ± 14.00	45.46 ± 13.49	40.47 ± 17.65	54.34 ± 21.04	
Maximum vertical joint reaction force (*N*) Mean (Stdv)					
Task (overall)					<0.001
Spine level (overall)					0.547
SLL	621.30 ± 232.98	719.94 ± 237.83	654.34 ± 206.41	880.44 ± 341.95	
LLUL	583.31 ± 223.96	681.14 ± 226.99	651.57 ± 157.85	844.58 ± 332.94	
ULLT	529.98 ± 212.83	625.63 ± 222.72	608.51 ± 118.51	801.12 ± 324.41	
LTLMT	499.55 ± 205.78	594.36 ± 213.38	586.87 ± 108.33	772.89 ± 316.53	
LMTUMT	474.58 ± 200.92	568.63 ± 207.30	566.72 ± 100.45	748.88 ± 312.91	
UMTUT	456.23 ± 196.54	549.40 ± 202.05	552.02 ± 96.32	731.64 ± 310.87	