Simulation of abdominal belt effects on IAP and spinal compressive force with musculoskeletal human model

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Abstract

Repeated High-G shocks and whole-body vibration (WBV) can increase the risk of fatigue and injuries in the lumbar region of the spine for crew and passengers on High-speed craft (HSC). Existing reviews have suggested the beneficial effects of abdominal belts regarding lumbar torso stabilization and spinal unloading. The paper provides a novel 3-D seated human model with a virtual belt to simulate the belt effects for occupants on HSC. The model is built with AnyBody, a commercial software for musculoskeletal simulation based on the inverse dynamics method. The belt behaves like an additional force exerted in the lumbar region, and the force magnitude has been optimized to avoid discomfort during long journeys. The belt effects have been studied with different levels of wave shock, anthropometries, and belt design parameters such as belt width and position. Wave shocks exerted on seat surface are considered to include both vertical and off-vertical (horizontal) acceleration and expressed with a half-sine pulse. The belt effects are evaluated with intra-abdominal pressure (IAP), transversus muscle activities, and spinal compressive force. The results have shown a combined increase of IAP (137% maximum) and a decrease of spinal compressive force at the L4/L5 joint (15.5% maximum) once the belt is applied under various circumstances. Transverse abdominis activity is also reduced with belt application. The belt performs best when it covers the entire lumbar region. Reduction of belt width might lead to increased muscle activity for the muscle that isn't covered by the belt, inducing over-recruited muscle. For the same belt width, belt position variations are irrelevant to the belt performance. It has been validated that the abdominal belt can significantly assist abdominal muscles and maintain a solid core during intense WBV generated in different sea states, reducing fatigue and the risk of injury to the lumbar. Therefore, the model can be a preliminary guide for designing the abdominal belt.

Keywords: Abdominal belt, whole-body vibration, high-G shock, intra-abdominal pressure, spinal compressive forces, muscle activity, high-speed craft.

Introduction

Repeated shocks and whole-body vibration always lead to detrimental effects on crew and passengers on high-speed craft (HSC) (Halswell, Wilson, Taunton, & Austen, 2016). Low back musculoskeletal injury is one of the most commonly seen symptoms for occupants with apparent muscle pains in the lumbar region (Bartleson, 2001; Bridger, 1999). Existing methods used to mitigate the symptom include limitations of the vehicle speed and improving the seat design for better vibration absorption (Cripps, Cain, Phillips, Rees, & Richards, 2003; Garme, Burstrom, & Kuttenkeuler, 2011; Myers et al., 2012; Townsend, Coe, Wilson, & Shenoi, 2012). However, these methodologies can increase the complexity and cost of the craft potentially. Therefore, protections on occupants with an abdominal belt was considered.

The abdominal belt was firstly considered as a support for athletes such as heavy weight lifters. The effect of the belt can be evaluated with intra-abdominal pressure (IAP), which is a parameter supposed to aid in reducing spinal disc compressive force (Grillner S Fau - Nilsson, Nilsson J Fau - Thorstensson, & Thorstensson). Harman *et al* did experiments on dead-lifting behaviour with and without a belt and compared the measured IAP (Harman, Rosenstein, Frykman, & Nigro, 1989). Significant increment of IAP was found after the belt was applied to stabilize the lumbar region. Similar conclusions were made, such as increasing intradiscal pressure (Miyamoto, Iinuma, Maeda, Wada, & Shimizu, 1996) and reduced spinal compressive force (Woldstad & R. Sherman, 1998). Although there existed controversial results that the belt did not contribute to the reduction of spinal compressive force (Ivancic, Cholewicki, & Radebold, 2002), no apparent findings showed that wearing a belt can either decrease IAP or increase the compressive force.

IAP and muscle forces are normally measured with transducers on human skin, and electromyography, which can cause potential injuries to the participants. It is also difficult to perform experiments with subjects exposed to extreme shock, such as those experienced on HSC. Therefore, the musculoskeletal model was created to simulate the muscle effects and body reactions to external shocks as an inexpensive and efficient method. De Zee *et al* built a lumbar model that can estimate the maximum extension moment in an upright position (de Zee, Hansen, Wong, Rasmussen, & Simonsen, 2007). An optimized model was later built by adding new elements to the model and was capable of estimating the muscle and tendon forces (Christophy, Faruk Senan, Lotz, & O'Reilly, 2012). Further studies have included the IAP effects, and the musculoskeletal model was coupled with Finite-element (FE) method (Liu, Khalaf, Adeeb, & El-Rich, 2019; Liu, Khalaf, Naserkhaki, & El-Rich, 2018). The results implied that the inclusion of IAP reduced global muscle forces, the disc loads and intradiscal pressure.

Based on the previous research, this paper has introduced a musculoskeletal model with virtual belts to simulate the belt effects for passengers on HSC with AnyBody Modelling System, a software for the development and analysis of the musculoskeletal system. Concerned parameters such as IAP, muscle activity, and spinal compressive force have been studied. In general, the abdominal belt can positively contribute to the stabilization of the core muscle in the lumbar region.

Methods

The seated human model was developed using AnyBody and depicted in **Figure 1A**. The chair was simplified as rigid to focus on the response of rigid components of the model during the force transmission. The real vibration was represented by vertical and off-vertical acceleration with different magnitudes. The signals were produced with a digital model (Olausson and Garme model) in MATLAB, as shown in **Figure 1B**. The half-sine pulse was fitted to a sine function (shown with **Equation 1**) and used as input in AnyBody to mimic the external vibration effects. In the equation, A represents the magnitude of the acceleration, and α is the shock wave amplitude.

$$A = \alpha \sin(\omega t + \varphi) \tag{1}$$

In the model, the lumbar region contained vertebra and transversus muscle. Five vertebra segments were included ranging from L1 to L5. As depicted in **Figure 1C**, the transversus muscle was connected to the vertebra, and the virtual belt will cover this region. The abdominal volume was idealized as a cylinder. In AnyBody, any force applied on the abdominal muscle can generate abdominal pressure. Therefore, the stretchy belt works like a virtual muscle with similar properties to the transversus muscle, but can provide a uniform inward force to help stabilize the lumbar region and generate IAP.

A B C

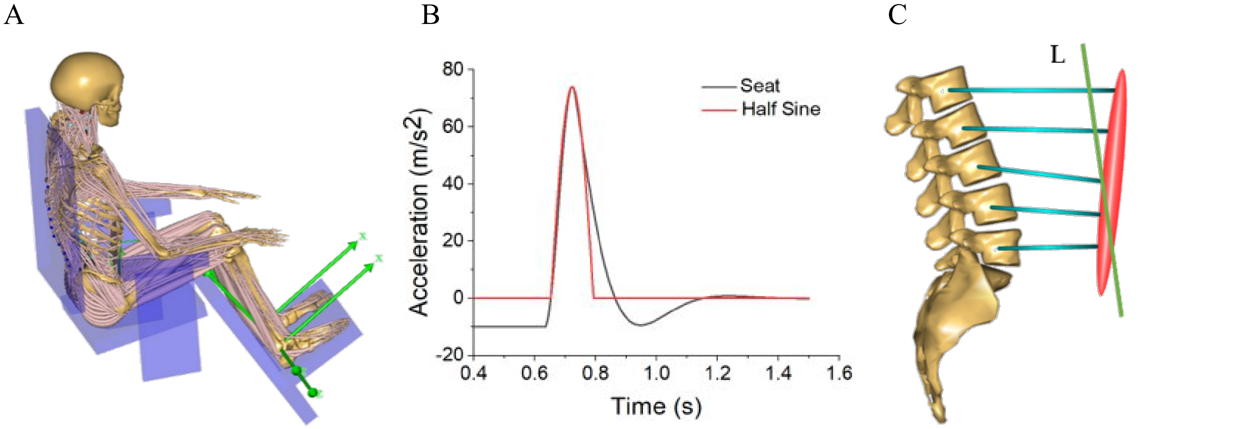

Figure 1. (A) A 3-D view of a seated human model in AnyBody software. (B) Half-sine pulse for simulation and the shock pulse on the seat surface. (C) Lumbar region structure with vertebra and transversus muscle.

In general, the numerical model was evaluated with shocks under different sea states ranging from 3g to 10g. Besides, occupants with different anthropometric dimensions were studied as well as different belt widths. Finally, both vertical and off-vertical accelerations with different amplitudes were simulated.

Results

Three main parameters were used to evaluate the effect of the abdominal belts, and results were obtained from the human MSK model. The first parameter is IAP, which is closely related to the stabilization of the lumbar region against external loading. The second one is the transversus muscle activity (TrA), which is calculated by dividing the actual muscle strength under vertical acceleration by the maximum muscle strength of the transvers abdominal muscle group. The maximum muscle strength is an inherent property of the muscle, and the value is constant. Therefore, muscle activity can represent muscle recruitment. The third is the spinal compressive force which is represented by a reaction force between adjacent vertebrae L4 and L5.

The three main results were initially shown in **Figure 2**, based on a seated human model experiencing 10g pure vertical acceleration with and without a belt. There was a significant increase in IAP (120%) after the belt was applied. Both the transversus muscle activity and L4/L5 compressive force were decreased with the virtual belt, indicating a positive effect of the belt application. These findings are consistent with the previous results that the back belt can enhance IAP and reduce measured back muscle electromyography (Kingma et al., 2020).

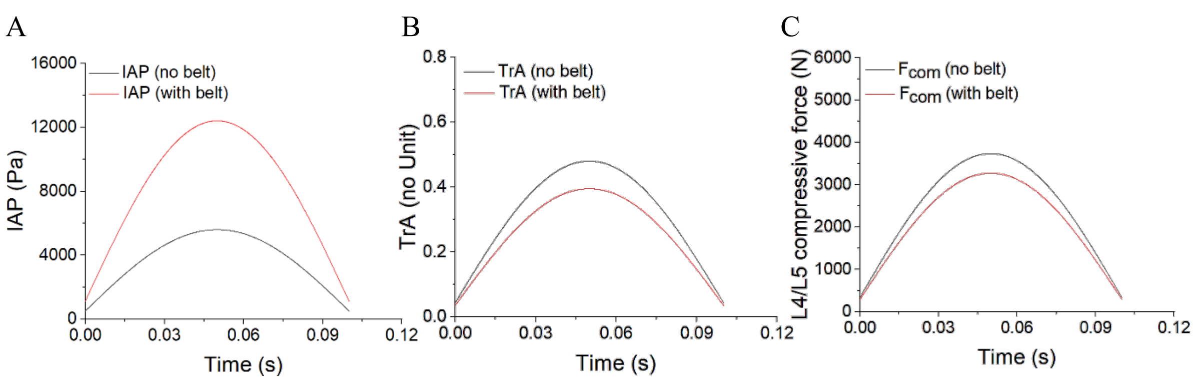

Figure 2. Belt effects on seated human model. (A) IAP value comparison. (B) Transversus muscle activity comparison. (C) Comparison of compressive force at L4/L5 joint.

The belt effects under different sea states were tested with data from previous literature (Riley, Haupt, Ganey, & Coats, 2018). A total of six levels of vertical acceleration were selected, ranging from 3g to 10g. in **Figure 3**, the maximum values of IAP, TrA, and L4/L5 compressive forces were evaluated under different vertical accelerations. As expected, the belt had an overall beneficial effect on all sea states. Similar results were found for people with different anthropometric dimensions. As displayed in **Table 1**, there was a significant reduction of compressive forces at L4/L5 joint after the belt was applied for 5%, 50%, and 95% anthropometric dimensions.

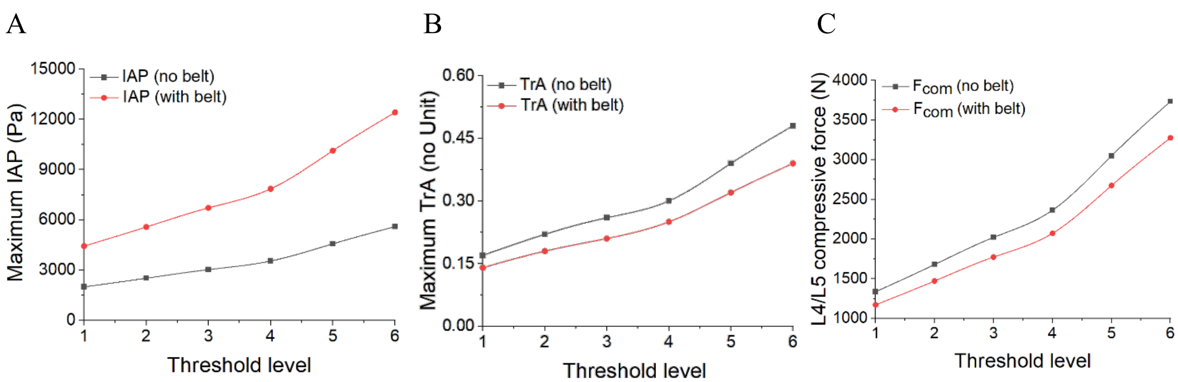

Figure 3. Belt influences under different vertical accelerations. (A) Maximum IAP comparison. (B) Maximum transversus muscle activity comparison. (C) Maximum compressive force at L4/L5 joint comparison.

Table 1. Belt effects for a human model with different anthropometric dimensions

	5th percentile	50th percentile	95th percentile
Body weight/height	69kg/169.3mm	81kg/178.1mm	96kg/189.8mm
IAP	+114%	+121%	+107%
TrA	-21.5%	-17.7%	-14.7
L4.L5 force	-12%	-12.3%	-10.3%

Values in the table are the differences before and after the belt was applied expressed in percentage; '+' indicates increased value, and '-' indicates reduced value.

The belt width effects were also studied. There are five vertebrae segments in the lumbar region; the belt width levels were represented by the number of segments covered by the abdominal belt. **Figure 4** shows that a level 5 belt width had the best belt performance, i.e., a belt that covers the entire lumbar region.

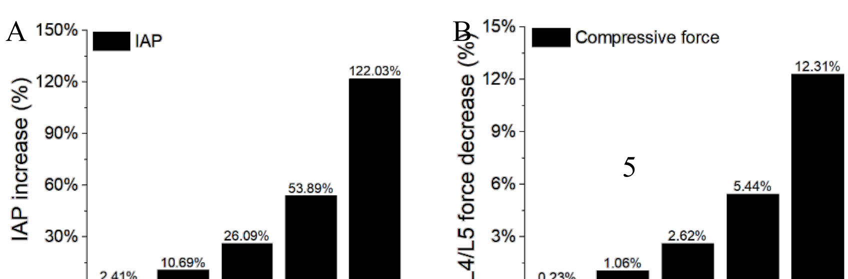

Figure 4. Belt width levels influence on (A) IAP increase. (B) L4/L5 compressive force decrease.

When the off-vertical acceleration was included, there was a significant increase in the spinal compressive force, indicating larger pressure on the human spine compared to pure vertical acceleration. To test the effects of off-vertical acceleration, six cases were tested and compared with vertical-only conditions (shown in **Table 2**). Composite values for the total acceleration for all cases were kept the same at 10g. Belt effects were shown in **Figure 5**; compared to pure vertical acceleration, the belt had a larger effect in both increase of IAP and the reduction of compressive force. However, large lateral acceleration can lead to the transverse abdominis activity value higher than 1, inducing a significant drop in the belt effects expressed with red dots in the figure.

Table 2. Parameters used for off-vertical acceleration.

Case	V (vertical)	L1(Lateral 1)	L2	L3	L4	L5	L6
Vertical acceleration (g)	10	9.98	9.95	9.88	9.8	9.54	8.66
Lateral acceleration (g)	0	0.5	1	1.5	2	3	5

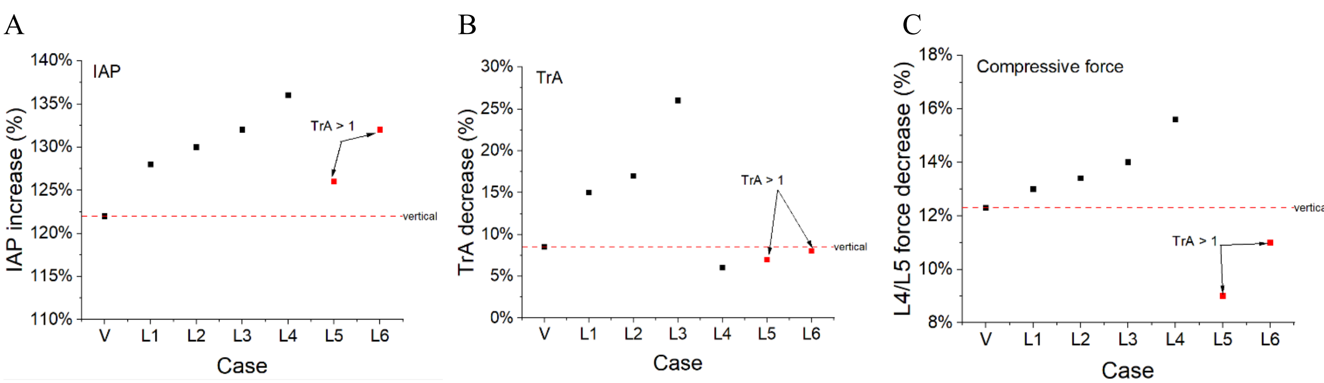

Figure 5. Belt effects on off-vertical acceleration. (A) IAP increment. (B) Transverse abdominis activity decrease. (C) L4/L5 compressive force decrease.

Discussion and Conclusions

For all of the shock conditions tested, the abdominal belt reduced the spinal loading in the lumbar region. This decrease in loading was due to the load being partially supported by the IAP. In no case did the belt make the response to the shock more severe in the lumbar region, thereby indicating a protective effect.

When the belt covers the entire lumbar region, all the transversus abdominis have the same muscle activity. However, a reduction of belt width might lead to increased muscle activity for the muscle that was not covered by the belt, and the increment value is inversely proportional to the number of muscles not covered by the belt. When the belt covered four vertebra segments, the activity of the unconstrained muscle increased by 60%, which can be over-recruited. This finding supports the result that the abdominal belt performed best when it covered the entire lumbar region.

With large values of lateral acceleration, the transverse abdominis activity can be higher 1, indicating that the muscle is not capable of responding to the shock, suggesting a limited value for shock exposure. Beyond the threshold of 1, the modelling indicates non-linear responses and the accuracy of the model is not guaranteed. Lateral acceleration also led to a potential threat to the human model with much higher spinal compressive forces; better belt effects compared to vertical-only acceleration implies that the belt can provide multi-axis support.

AnyBody is a modelling tool that is capable of simulating musculoskeletal loading and therefore allows for the analyses reported here. However, it has a limitation, such that it does not simulate the dynamic motion of segments and associated geometric non-linearities. Non-linearities of apparent mass and transmissibility under WBV reflected by changes in resonance frequency can be studied with experimental measurements and numerical simulation (Coe, Xing, Shenoi, & Taunton, 2009; Mansfield & Griffin, 2000; Shabana, Gantoi, & Brown, 2011). Besides, the belt model was limited to simulating only stretchy belts that provided a constant inward force, rather than a body reacting to the presence of a non-stretch belt around the abdomen. The belt is also an idealized cylinder, with no variation in width or rigid design elements that may be present in a physical product. In order to model these, a different approach would be needed, potentially building more complex models combining active elements and finite element analysis (FEA).

In this paper, a novel biomechanical model was built with AnyBody software to study potential belt protection for seated humans on HSC. The impact of the belt was evaluated by IAP, muscle activities and spinal compressive forces. The results have shown a combined increase of IAP (137% maximum) and a decrease of spinal compressive force at the L4/L5 joint (15.5% maximum) once the belt is applied under various circumstances, including vertical and off-vertical acceleration. To achieve the best belt performance, the belt should cover the full range of the lumbar region, which is also comfortable for a human being. This study can provide a preliminary guide to the design of an abdominal belt to protect occupants on the HSC.

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