Riding the waves: Kidney belt-mounted accelerometers to measure lumbar spine vibrations in high-speed craft occupants

Pahansen de Alwis
RISE Report : 2023:136
Riding the waves: Kidney belt-mounted accelerometers to measure lumbar spine vibrations in high-speed craft occupants

Pahansen de Alwis
Abstract

The scientific investigation into the viability of employing kidney-belt-mounted accelerometers to quantify shock and vibration exposure in the lumbar spine region of occupants in high-speed marine craft, and their concordance with prevailing standards, has been heretofore unexplored. Addressing this research gap, a series of meticulously designed laboratory and field experiments were undertaken.

In the laboratory setting, two test subjects were engaged in predefined body movements, with accelerations recorded using both body-mounted and kidney-belt-mounted accelerometers. This controlled environment allowed for a comparative analysis of the efficacy of the two accelerometer configurations in capturing lumbar spine accelerations.

Field experiments expanded upon these findings, involving the recording of acceleration exposures during a high-speed marine craft exercise. The kidney-belt-mounted accelerometers were utilized alongside seat-mounted accelerometers to assess their applicability in real-world dynamic conditions.

The results revealed that kidney-belt-mounted accelerometers effectively captured lumbar spine accelerations during basic body movements, particularly when the torso was maintained in an upright position. However, the translation of these measurements into a framework aligned with existing international standards encountered substantial challenges during the field experiment.

This study underscores the potential utility of kidney-belt-mounted accelerometers for lumbar spine acceleration measurement in controlled environments. Nevertheless, the complexities associated with aligning these measurements with established international standards were evident, highlighting the need for further consideration and refinement.

The implications of this research extend to the recognition that current standards may not fully address the intricacies of shock and vibration exposure in the lumbar spine region within the dynamic context of high-speed marine craft environments. Consequently, there is a clear call for the development of standards specifically tailored to these operational conditions to ensure a comprehensive and accurate assessment of lumbar spine health in marine craft occupants.

Keywords: High-speed craft, whole-body vibration, musculoskeletal pain
Content

Abstract .............................................................................................................................................. 1
Content................................................................................................................................................ 2
Preface .................................................................................................................................................. 3
Summary ................................................................................................................................................ 4
1 Introduction ......................................................................................................................................... 5
2 Methods ............................................................................................................................................. 7
    2.1 Laboratory experiments .............................................................................................................. 7
        2.1.1 Participants .......................................................................................................................... 7
        2.1.2 Instrumentation .................................................................................................................... 7
        2.1.3 Procedure ............................................................................................................................ 8
    2.2 Field experiment .......................................................................................................................... 9
        2.2.1 Participants .......................................................................................................................... 9
        2.2.2 Instrumentation .................................................................................................................... 9
    2.3 Data analysis ............................................................................................................................... 9
        2.3.1 Cross-correlation analysis ................................................................................................... 9
3 Results ............................................................................................................................................. 11
    3.1 Laboratory experiments .............................................................................................................. 11
    3.2 Field experiment ........................................................................................................................ 12
4 Discussion ......................................................................................................................................... 14
    4.1 Laboratory experiment .............................................................................................................. 14
    4.2 Field experiment ........................................................................................................................ 14
    4.3 Implications for vibration assessment ...................................................................................... 15
5 Conclusions ....................................................................................................................................... 16
6 Acknowledgements ........................................................................................................................ 17
7 References ......................................................................................................................................... 18
Preface

This research report, titled “Riding the waves: Kidney belt-mounted accelerometers to measure lumbar spine vibrations in high-speed craft occupants”, is presented with enthusiasm. The study addresses a significant gap in scientific literature by investigating the viability of using kidney-belt-mounted accelerometers to measure shock and vibration exposure in the lumbar spine region, particularly in the context of high-speed marine craft (HSMC) occupants.

The motivation behind this research emanates from the occupational challenges faced by HSMC operators, who are exposed to whole-body vibration and repeated shock, contributing to an increased risk of lower back pain. Despite the prevalence of this issue, existing international standards primarily rely on seat pad measurements, which may not accurately capture the impact on the lumbar spine region. This research seeks to explore an alternative approach by employing kidney-belt-mounted accelerometers.

The collaboration between the RISE Research Institutes of Sweden, the KTH Royal Institute of Technology, and the Swedish Coast Guard underscores the interdisciplinary nature of this endeavor. A series of laboratory and field experiments were conducted to assess the effectiveness of kidney-belt-mounted accelerometers in measuring lumbar spine accelerations during basic body movements and high-speed marine craft exercises.

Promising results were observed in laboratory experiments, demonstrating the capability of kidney-belt-mounted accelerometers to effectively measure lumbar spine accelerations during various body movements. However, challenges in evaluating vibration exposures using existing international standards were encountered in the field experiments, emphasizing the need for further exploration in real-world scenarios.

This report provides a detailed account of the research methodology, including participant recruitment, instrumentation, and data analysis. The findings highlight the potential of kidney-belt-mounted accelerometers while also acknowledging the complexities and limitations associated with their use in the field.

Sincere gratitude is extended to the participants of the study, the Swedish Coast Guard for their collaboration, and the KTH BioMEx Center and Hugo Hammars fond för sjöfartsteknisk forskning for funding this research project. Their contributions have been integral to the success of this study.

As readers delve into the pages of this report, they are invited to join the exploration of the innovative use of kidney-belt-mounted accelerometers and their implications for assessing lumbar spine shock and vibration on HSMC occupants. May this research contribute to the development of more effective strategies for mitigating the adverse effects of whole-body vibration and repeated shock in this challenging occupational setting.

Pahansen de Alwis
Summary

The research project conducted collaboratively by the RISE-Research Institutes of Sweden, the KTH Royal Institute of Technology, and the Swedish Coast Guard, aimed to investigate the potential of kidney-belt-mounted accelerometers in measuring lumbar spine vibrations during various body movements and high-speed marine craft operations.

The introduction highlights the occupational challenges faced by high-speed marine craft (HSMC) operators, emphasizing the increased risk of lower back pain due to whole-body vibration and repeated shock. With existing international standards relying on seat pad measurements, the study explores kidney-belt-mounted accelerometers as an alternative method for a more accurate assessment of lumbar spine vibrations.

The laboratory experiments involved two healthy subjects performing predefined body movements while accelerations were measured using body-mounted and kidney-belt-mounted accelerometers. The results demonstrated a notable cross-correlation between the two sets of accelerometer signals, suggesting the potential effectiveness of kidney-belt-mounted accelerometers in measuring lumbar spine vibrations during basic body movements. However, challenges related to temporal discrepancies and the influence of torso bending and twisting were identified, indicating the need for further exploration.

In the field experiment, conducted in collaboration with the special operations unit of the Swedish Coast Guard during a two-day high-speed marine craft exercise, craft operators were instrumented with kidney-belt-mounted accelerometers. Distinct cross-correlation peaks were observed between seat-mounted and kidney-belt-mounted accelerometer signals. Challenges, including lower magnitudes and instability in the navigator’s signals, were noted. The absence of supplementary data detailing specific bodily movements in the field experiment prompted recommendations for future studies, such as integrating video cameras and subjective information collection.

The discussion section delves into the implications and challenges revealed by both laboratory and field experiments. It emphasizes the need for further research to integrate local iliac spine accelerations into existing ISO standards, accommodating the varied body postures inherent in marine craft operations. Practical challenges, system resilience concerns, and the exploration of wireless Inertial Measurement Units (IMU sensors) are discussed, offering insights into potential advancements in vibration assessment methodologies.

In conclusion, the project report provides a comprehensive exploration of the feasibility of kidney-belt-mounted accelerometers in assessing lumbar spine vibrations on high-speed marine craft occupants. The findings contribute valuable insights to the scientific community, highlighting the potential applications and limitations of this methodology. The recommendations for future research underscore the ongoing pursuit of innovative solutions to enhance vibration assessment in the challenging occupational setting of high-speed marine craft operations.
1 Introduction

High-Speed Marine Craft (HSMC) operators are exposed to a range of challenging and adverse conditions as a result of their occupation. The nature of their work involves multiple interacting factors that can significantly impact their well-being and physical health. In particular, exposure to whole-body vibration accompanied by repeated shock has emerged as a distinct factor that elevates the risk of lower back pain among these individuals [1-10]. This issue has far-reaching implications not only for the health and safety of HSMC occupants but also for their overall job performance and quality of life.

It’s noteworthy that seaborne populations, including those in HSMCs, have been granted an exemption from the statutory vibration exposure limit values. The rationale behind this exemption is the assertion that complying with these limits is currently infeasible, given the available technology and the inherent demands of their occupation [11]. Nevertheless, a pressing concern remains – even when equipped with shock-mitigation systems, HSMC occupants consistently find themselves exceeding these statutory limit values during their routine work operations [12]. This situation underscores the urgent need to explore alternative methods for measuring and addressing the issue of whole-body vibration and its potential impact on the lumbar spine region, particularly in the context of HSMCs.

The existing international standards for evaluating human exposure to mechanical multiple shocks primarily rely on seat pad measurements, which are taken when an individual is in a seated position. While these standards serve as valuable guidelines for assessing and managing exposure to mechanical shocks, it has become increasingly evident that there is a strong association between vibration exposure and lower back pain [13-15]. As a result, there has been a growing inclination to adopt kidney-belt-mounted accelerometers to provide a closer and more accurate measurement of the vibrations that affect the lumbar spine region [16-19]. This shift is justified, in part, by referring to the lumbar spine response model used in the aforementioned standards, which suggests that the most precise measurement of lumbar peak acceleration can be achieved by placing the accelerometer in proximity to the lumbar region. However, what is surprising is that no substantial scientific evidence exists in the current literature to validate the efficacy and reliability of using kidney-belt-mounted accelerometers in measuring human shock and vibration exposure on mobile platforms, and more importantly, in evaluating these measurements using the existing standards.

Moreover, a series of factors and challenges associated with the use of kidney-belt-mounted accelerometers have not been thoroughly addressed in previous studies. Soft tissue artefacts, which can affect the accuracy of measurements, are one such concern [20-22]. Additionally, the relative changes in accelerometer orientation attributable to the placement on a kidney belt have not been adequately considered in previous research endeavours [16-19]. These challenges underscore the need for a comprehensive exploration of the feasibility and practicality of this measurement approach.

Furthermore, it is crucial to recognize that the existing standard [14] assumes that the individual subjected to vibration remains seated in an upright position throughout the
exposure period. However, this assumption may not align with the real-life scenarios experienced by HSMC operators where one of the most common reactions when these operators encounter oncoming waves is to stand rather than remain seated. This discrepancy between the standard's assumptions and the actual circumstances faced by HSMC occupants highlights the importance of examining the utility and accuracy of kidney-belt-mounted accelerometers, especially when individuals are not in contact with their seats.

In light of these challenges and uncertainties, a collaborative research effort was initiated, bringing together the expertise of the RISE-Research Institutes of Sweden, the KTH Royal Institute of Technology, and the Swedish Coast Guard. The primary aim of this collaboration was to conduct a series of experiments to explore the feasibility of using kidney-belt-mounted accelerometers for measuring shock and vibration experienced in the lumbar spine region of HSMC occupants. This research was conceived to provide a more comprehensive and empirical understanding of the practicality and accuracy of this novel measurement approach, particularly within the unique and demanding conditions encountered by high-speed marine craft operators. The insights gained from this investigation hold the potential to inform the development of more effective strategies and guidelines for mitigating the adverse effects of whole-body vibration and repeated shock on HSMC occupants, ultimately enhancing their well-being and performance in this challenging occupational setting.
2 Methods

The study encompassed a series of laboratory and field experiments designed to investigate the feasibility of utilizing kidney belt-mounted accelerometers for measuring accelerations experienced by high-speed marine craft occupants, both in controlled laboratory conditions and in real-world field scenarios.

2.1 Laboratory experiments

2.1.1 Participants

Two healthy subjects were recruited for the laboratory experiments, which were conducted at a KTH Royal Institute of Technology Sweden test facility. These experiments were carried out on three separate occasions, referred to as day-1, day-2, and day-3, with each session spaced two weeks apart.

2.1.2 Instrumentation

For the laboratory experiments, two vibration measurement systems, each consisting of three tri-axis accelerometers, a GPS antenna, and a data acquisition unit, were employed. These systems recorded acceleration data at 600Hz and GPS data at 1Hz, storing them in local memory. In these experiments, two detachable tri-axial accelerometers were affixed to the palpable bony landmarks, specifically the left and right posterior-superior iliac spine of the subjects, using double-sided tape.

![Instrumentation of subjects (posterior view), (a) and (b) - laboratory experiment (c) - field experiment](image)

**Figure 1.** Instrumentation of subjects (posterior view), (a) and (b) - laboratory experiment (c) - field experiment
This placement allowed for the measurement of accelerations in close proximity to the lumbar spine region and served as a reference. Additionally, a kidney belt was secured around the lower torso of the subjects, covering the accelerometers attached to the iliac spine. Two other detachable tri-axial accelerometers from the remaining measurement system were attached to the kidney belt using 3M™ Dual-Lock™ reclosable fasteners, directly above the accelerometers positioned on the iliac spine as shown in Figure 1 (a), (b), and (c).

2.1.3 Procedure

The laboratory experiments involved a set of five predefined body movements, with one-minute intervals between each movement (see Table 1). One subject underwent testing on day-1 and day-2, while the other subject was tested on day-3. On day-1 and day-3, two sessions were conducted, each comprising three rounds of five body movements with adequate rest intervals. The accelerometers were detached from their data acquisition units during these breaks. On day-2, after the second session, the kidney belt was removed and then worn again by the subject for an additional session. Notably, the subject also engaged in a one-hour outdoor brisk walk during the break on day-3.

Table 1. Laboratory experiment schedule

<table>
<thead>
<tr>
<th>Day</th>
<th>Subject No.</th>
<th>Body movement</th>
<th>Repetitions</th>
<th>Round-1</th>
<th>Round-2</th>
<th>Round-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Session-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jump</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Step on/off</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Squat</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Walk</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jog</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-hour break</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Session-2 was the same as Session-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2-week break</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Session-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>was the same as Session-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-hour break</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Session-4 was the same as Session-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unfasten and fasten the kidney belt by the subject</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Session-5 was the same as Session-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2-week break</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Session-6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>was the same as Session-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3-hour break with a 1-hour brisk walk</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Session-7 was the same as Session-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Jump: Jump from a platform with a height of 0.5m while keeping the feet together, placing arms across the chest with hands touching opposite shoulders and keeping the torso as upright as possible.  
Step on/off: Step onto and off from the same platform while placing arms across the chest with hands touching opposite shoulders and keeping the torso as upright as possible. Use the same leg to step on and off. Perform five repetitions with the right leg and five with the left leg.  
Squat: Perform ordinary squats while placing arms across the chest with hands touching opposite shoulders and keeping the torso as upright as possible.  
Walk: Walk a 10m distance marked on the floor up and down for 5 rounds.  
Jog: Jog a 10m distance marked on the floor up and down for 5 rounds.
2.2 Field experiment

The field experiment was conducted in collaboration with the special operations unit of the Swedish Coast Guard, during a two-day high-speed marine craft exercise.

2.2.1 Participants

Two craft operators, comprising a driver and a navigator, voluntarily participated in the field experiment while operating a special high-speed rigid inflatable boat (RIB).

2.2.2 Instrumentation

For the field experiment, the two craft operators were instrumented with kidney belt-mounted accelerometers. The two detachable tri-axial accelerometers from the vibration measurement system were attached to the subjects’ kidney belts, aligned with the left and right posterior-superior iliac spine, while installing the non-detachable tri-axial accelerometer from the same system on the subject’s seat frame.

2.3 Data analysis

2.3.1 Cross-correlation analysis

The unbiased normalized cross-correlation of two acceleration signals, $x(t)$ and $y(t)$, was numerically computed using Equation (1). To assess the relationship between the body-mounted and kidney-belt-mounted accelerometer signals, cross-correlations were calculated for each body movement in the laboratory experiments. Moreover, cross-correlations were computed between the seat-mounted and kidney-belt-mounted accelerometer signals, as well as between the two kidney-belt-mounted accelerometer signals, using a one-minute non-overlapping time window that moved across the entire time history for each day of the field experiment.

$$
\tilde{R}_{xy}(\tau) = \frac{1}{\sqrt{R_{xx}(0) \cdot R_{yy}(0)}} \cdot \frac{1}{N - |\tau|} \cdot \frac{1}{N+\tau} \sum_{t=1}^{N-\tau} x(t) \cdot y(t - \tau) - \frac{1}{N+\tau} \sum_{t=1}^{N+\tau} x(t - \tau) \cdot y(t)
$$

(1)

where,
- $\tilde{R}_{xy}$ - unbiased normalized cross-correlation between $x$ with $y$ signals
- $R_{xx}(0)$ - autocorrelation of $x$ signal at zero lag
- $R_{yy}(0)$ - autocorrelation of $y$ signal at zero lag
- $\tau$ - sample number
- $\tau$ - number of samples lagging or leading
- $N$ - number of samples

The vector sum of the $x$, $y$, and $z$ directional acceleration signals was employed to compute the cross-correlations, as outlined below.
\[ a(t) = \sqrt{a_x^2(t) + a_y^2(t) + a_z^2(t)} \] (2)

where,
\( a(t) \) - vector sum of instantaneous acceleration in \( ms^{-2} \)
\( a_x(t) \) - instantaneous acceleration with respect to the \( x \)-axis in \( ms^{-2} \)
\( a_y(t) \) - instantaneous acceleration with respect to the \( y \)-axis in \( ms^{-2} \)
\( a_z(t) \) - instantaneous acceleration with respect to the \( z \)-axis in \( ms^{-2} \)
## 3 Results

### 3.1 Laboratory experiments

In the laboratory experiments, a robust cross-correlation peak was consistently observed between the body-mounted and kidney-belt-mounted accelerometer signals for each body movement studied. The values for the cross-correlation coefficient ($R_{xy}$) ranged from 0.9 to 1.0 in activities such as jumping, stepping on/off, walking, and jogging, while in squatting, $R_{xy}$ ranged from 0.8 to 1.0 (see Table 2).

<table>
<thead>
<tr>
<th>Day</th>
<th>Session</th>
<th>Body movement</th>
<th>Repetitions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>R1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Left&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$R_{xy}$ $\tau$ [s]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Left&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$R_{xy}$ $\tau$ [s]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Left&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$R_{xy}$ $\tau$ [s]</td>
</tr>
</tbody>
</table>

| Day-1 | Session-1 | Jump | 1.0 | 3.7 | 1.0 | 3.7 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 3.7 | 1.0 | 3.7 |
|       |           | Step  | 0.9 | 3.7 | 0.9 | 3.7 | 0.9 | 3.7 | 0.9 | 3.7 | 0.9 | 3.7 | 0.9 | 3.7 |
|       |           | Squat | 0.9 | 3.7 | 0.9 | 3.7 | 0.9 | 0.4 | 0.4 | 0.4 | 0.9 | 3.7 | 0.9 | 3.7 |
|       |           | Walk  | 1.0 | 3.7 | 1.0 | 3.7 | 1.0 | 3.7 | 1.0 | 3.7 | 1.0 | 3.7 | 1.0 | 3.7 |
|       |           | Jog   | 1.0 | 3.7 | 1.0 | 3.7 | 1.0 | 3.7 | 1.0 | 3.7 | 1.0 | 3.7 | 1.0 | 3.7 |
| Day-1 | Session-2 | Jump | 1.0 | 3.6 | 1.0 | 3.6 | 1.0 | 3.6 | 1.0 | 3.6 | 1.0 | 3.6 | 1.0 | 3.6 |
|       |           | Step  | 1.0 | 3.6 | 1.0 | 3.6 | 0.9 | 3.6 | 0.9 | 3.6 | 1.0 | 3.6 | 1.0 | 3.6 |
|       |           | Squat | 0.9 | 3.6 | 0.9 | 3.6 | 0.9 | 3.6 | 0.9 | 3.6 | 0.9 | 3.6 | 0.9 | 3.6 |
|       |           | Walk  | 1.0 | 3.6 | 1.0 | 3.6 | 1.0 | 3.6 | 1.0 | 3.6 | 1.0 | 3.6 | 1.0 | 3.6 |
|       |           | Jog   | 1.0 | 3.6 | 1.0 | 3.6 | 1.0 | 3.6 | 1.0 | 3.6 | 1.0 | 3.6 | 1.0 | 3.6 |
| Day-1 | Session-3 | Jump | 1.0 | 3.3 | 1.0 | 3.3 | 1.0 | 3.3 | 1.0 | 3.3 | 1.0 | 3.3 | 1.0 | 3.3 |
|       |           | Step  | 1.0 | 3.3 | 1.0 | 3.3 | 1.0 | 3.3 | 1.0 | 3.3 | 1.0 | 3.3 | 1.0 | 3.3 |
|       |           | Squat | 0.9 | 3.3 | 0.9 | 3.3 | 0.9 | 3.3 | 0.9 | 3.3 | 0.9 | 3.3 | 0.9 | 3.3 |
|       |           | Walk  | 0.9 | 3.3 | 1.0 | 3.3 | 0.9 | 3.3 | 0.9 | 3.3 | 0.9 | 3.3 | 0.9 | 3.3 |
|       |           | Jog   | 1.0 | 3.3 | 1.0 | 3.3 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 3.3 | 1.0 | 3.3 |
| Day-2 | Session-4 | Jump | 1.0 | 3.0 | 1.0 | 3.0 | 1.0 | 3.0 | 1.0 | 3.0 | 1.0 | 3.0 | 1.0 | 3.0 |
|       |           | Step  | 0.9 | 3.0 | 0.9 | 3.0 | 0.9 | 3.0 | 0.9 | 3.0 | 1.0 | 3.0 | 1.0 | 3.0 |
|       |           | Squat | 0.9 | 3.0 | 0.9 | 3.0 | 0.9 | 3.0 | 0.9 | 3.0 | 0.9 | 3.0 | 0.9 | 3.0 |
|       |           | Walk  | 1.0 | 3.0 | 1.0 | 3.0 | 0.9 | 3.0 | 0.9 | 3.0 | 1.0 | 3.0 | 1.0 | 3.0 |
|       |           | Jog   | 1.0 | 3.0 | 1.0 | 3.0 | 1.0 | 3.0 | 1.0 | 3.0 | 1.0 | 3.0 | 1.0 | 3.0 |
| Day-2 | Session-5 | Jump | 1.0 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 |
|       |           | Step  | 0.9 | 2.5 | 0.9 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 |
|       |           | Squat | 0.9 | 2.5 | 0.9 | 2.5 | 0.9 | 2.5 | 0.9 | 2.5 | 0.9 | 2.5 | 0.9 | 2.5 |
|       |           | Walk  | 1.0 | 2.5 | 0.9 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 |
|       |           | Jog   | 1.0 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 |
| Day-3 | Session-6 | Jump | 1.0 | -0.4 | 1.0 | -0.4 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | -0.4 | 1.0 | -0.4 |
|       |           | Step  | 1.0 | -0.4 | 1.0 | -0.4 | 0.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 |
|       |           | Squat | 1.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 |
|       |           | Walk  | 1.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 |
|       |           | Jog   | 1.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 | 1.0 | -0.4 |
| Day-3 | Session-7 | Jump | 0.9 | 2.7 | 0.9 | 2.7 | 0.9 | 2.7 | 1.0 | 2.7 | 1.0 | 2.7 | 1.0 | 2.7 |
|       |           | Step  | 0.9 | 2.7 | 0.9 | 2.7 | 0.9 | 2.7 | 0.9 | 2.7 | 0.9 | 2.7 | 0.9 | 2.7 |
|       |           | Squat | 0.9 | 2.7 | 0.9 | 2.7 | 0.9 | 2.7 | 0.9 | 2.7 | 0.9 | 2.7 | 0.9 | 2.7 |
|       |           | Walk  | 1.0 | 2.7 | 1.0 | 2.7 | 1.0 | 2.7 | 1.0 | 2.7 | 1.0 | 2.7 | 1.0 | 2.7 |
|       |           | Jog   | 1.0 | 2.7 | 1.0 | 2.7 | 0.9 | 2.7 | 0.9 | 2.7 | 1.0 | 2.7 | 1.0 | 2.7 |

* - Time difference between body-mounted and kidney-belt-mounted accelerometer signals. $\tau$ is positive when the kidney-belt-mounted accelerometer signal is leading and negative when it is lagging.

+ bilateral sides of the body, posterior view.
Notably, unfastening and fastening the kidney belt during the experiment did not result in any noticeable effects on the correlations. Furthermore, throughout the entire laboratory experiment, a time lag between 0 and 3.7 seconds was identified between the body-mounted and kidney-belt-mounted accelerometer signals. This temporal shift was consistently observed across all three experimental days.

### 3.2 Field experiment

In the field experiment, the craft operated at sea for approximately eleven hours and twenty minutes on the first day and ten hours and ten minutes on the second day. Notably, the magnitudes of vibration exposure experienced on board the craft were found to be notably lower compared to those observed in similar studies [1, 3, 12].

Figure 2 depicts the maximum cross-correlation peak observed between the seat-mounted and kidney-belt-mounted accelerometer signals. The operational time of the craft during both days was approximately six hours, with the craft remaining stationary for most of the remaining time.

![Figure 2](image_url)

**Figure 2.** Cross-correlation between seat-mounted and kidney-belt-mounted accelerometer signals and between the left and right kidney-belt-mounted accelerometer signals of the driver and navigator during the first and second days.
However, it is important to note that during certain periods, inexplicable anomalous behaviour was observed in the kidney-belt-mounted accelerometer signals as shown in Figure 3, and these segments of the signals were subsequently excluded during data processing.

![Figure 3. Inexplicable anomalous behaviour of the kidney-belt-mounted accelerometer signals.](image)

The results from the field experiment revealed that the maximum cross-correlation between the seat-mounted and kidney-belt-mounted accelerometer signals of both the driver and navigator on both days was predominantly below 0.9 and exhibited temporal instability. Specifically, fluctuations around 0.1 and 0.9 were observed, particularly at the beginning and end of the marine exercise, such as while passing the fairway and in the middle of the exercise.

On the first day, the left and right kidney-belt-mounted accelerometer signals of the driver demonstrated a relatively stable maximum cross-correlation, closer to 1.0. However, on the second day, these signals exhibited increased instability, fluctuating mostly between 0.9 and 1.0. It is noteworthy that the driver's accelerometer signals consistently exhibited a relatively stable maximum cross-correlation compared to those of the navigator. Importantly, no time delays were observed between the accelerometer signals recorded during the field experiment.
4 Discussion

The feasibility of employing kidney-belt-mounted accelerometers for the assessment of lumbar spine vibrations in high-speed marine craft occupants was investigated through a series of laboratory and field experiments. Each experiment, while unique in its findings, contributed to a holistic understanding of the potential applications and limitations of this methodology.

4.1 Laboratory experiment

In the laboratory experiment, a notable cross-correlation peak was observed between the body-mounted and kidney-belt-mounted accelerometer signals, suggesting the potential effectiveness of this approach for the measurement of lumbar spine vibrations. However, a significant temporal discrepancy between the two sets of accelerometer signals was identified. The source of this temporal shift could be traced to a disparity in the time stamps generated by the two distinct vibration measurement systems employed in the experiment. It is important to acknowledge that these systems, originally designed for outdoor marine operations, relied on GPS for time stamp initiation and data recording. Nevertheless, the enclosed laboratory environment presented challenges for the GPS in connecting to satellites, resulting in temporal inconsistencies in the accelerometer data.

Additionally, it should be noted that the laboratory experiment was constrained to the examination of body movements with an upright torso. Further research is deemed necessary to explore how the performance of the kidney belt arrangement may be influenced by the bending and twisting of the torso, which are common in real-world scenarios.

4.2 Field experiment

The field experiment introduced another layer of insight into the kidney belt-mounted accelerometer methodology. While distinct cross-correlation peaks were observed between the seat-mounted and kidney-belt-mounted accelerometer signals, these peaks exhibited lower magnitudes and a degree of instability when compared to the cross-correlation of the left and right kidney-belt-mounted accelerometer signals. The precise cause of these anomalies, particularly the fluctuating cross-correlation peaks in the navigator’s kidney-belt-mounted signals, remained elusive due to the absence of supplementary data detailing specific bodily movements beyond the recorded accelerations.

To address these knowledge gaps, future studies could consider the integration of video cameras within the measurement system and the collection of subjective information through questionnaires or post-experiment interviews. Such additional data could provide valuable context and insights into the behaviour of accelerometer signals in a real-world marine craft environment.

However, it is crucial to acknowledge that the absence of body-mounted accelerometers in the field experiment limited the ability to determine the accuracy of measuring acceleration near the lumbar spine using the kidney belt arrangement during high-
speed marine operations. Despite this limitation, no temporal disparities were observed in the acceleration signals. This finding affirmed seamless communication between the GPS units of both systems and the satellite network during the marine exercise. Nevertheless, concerns have been raised about system resilience and data reliability due to the unexplained irregular behaviour of the kidney belt-mounted accelerometers on specific occasions.

Moreover, the laboratory experiment emphasized the practical challenges associated with performing simple body movements while wearing a kidney belt, particularly when connected to a data acquisition unit with multiple cables. Additionally, the difficulty in routing cables through the overalls of the craft operators during the field experiment and the need for assistance in aligning kidney-belt-mounted accelerometers with the iliac spine underscore the importance of careful supervision during instrumentation.

4.3 Implications for vibration assessment

The combined findings from both experiments bear significant implications for the assessment of vibrations, particularly in the specific context of high-speed marine craft. These results highlight notable limitations within the existing ISO standards that rely on recurrent artificial neural networks to model z-axis lumbar acceleration responses. These standards are predicated on an assumption of an upright seated posture without back support, a condition that may not align directly with the evaluation of accelerations measured at the iliac spine using the kidney belt arrangement.

The observed disparities underscore the need for further research to refine and incorporate the use of local iliac spine accelerations into existing standards. Such an evolution is paramount for enabling the assessment of vibration exposures across a spectrum of various body postures, a critical consideration in the dynamic operational scenarios of marine craft.

Furthermore, this study advocates for the exploration of technologically advanced and user-friendly alternatives to kidney-belt-mounted accelerometers. The advent of wireless Inertial Measurement Units (IMU sensors) introduces streamlined and wire-free options for data collection. These devices, equipped with the capacity to synchronize data with precise time stamps upon retrieval, present opportunities for extending measurement capabilities beyond the confines of the lumbar spine region. However, the adoption of these innovations necessitates a methodical re-evaluation of existing protocols for assessing vibration exposure, ensuring seamless integration and optimization of these evolving technological features.

This study underscores the imperative for refining existing standards to encompass local iliac spine accelerations, thereby enabling a more comprehensive evaluation of vibration exposures across diverse body postures relevant to high-speed marine craft operations. Additionally, the consideration of wireless IMU sensors presents a promising avenue for future research, albeit requiring a meticulous re-evaluation of assessment methodologies to accommodate the evolving landscape of measurement technologies.
5 Conclusions

In summary, this study systematically explored the applicability of kidney-belt-mounted accelerometers for assessing shock and vibration exposure in the lumbar spine region of high-speed marine craft occupants through both laboratory and field experiments.

The laboratory experiment demonstrated the efficacy of the kidney belt configuration in accurately measuring vibrations proximal to the lumbar spine during basic body movements. This underscores the potential utility of kidney-belt-mounted accelerometers for controlled assessments of lumbar spine accelerations.

However, the field experiment revealed a notable challenge in applying established international standards to evaluate vibration exposures measured with the kidney belt arrangement. This highlights the necessity for specialized standards tailored to the dynamic conditions inherent in high-speed marine craft environments.

Additionally, the study advocates for further research focusing on establishing correlations between lumbar spine vibrations and those in other anatomical regions. Such investigations are crucial for a comprehensive understanding of the implications of shock and vibration exposure on psychophysical health and performance in high-speed marine craft occupants.

To enhance the accuracy and reliability of future investigations, the integration of cutting-edge motion measurement devices is recommended. This technological refinement aims to strengthen the precision of data collection, contributing to a more nuanced understanding of the complex dynamics involved in lumbar spine acceleration measurement.

In conclusion, while affirming the potential of kidney-belt-mounted accelerometers in controlled settings, this study emphasizes the imperative for specialized standards and continued research efforts to advance the comprehension of the effects of vibrations in high-speed marine craft environments.
6 Acknowledgements

Acknowledgements to the Swedish Coast Guard for providing a high-speed marine craft and crew for the field experiment. The KTH BioMEx Center and Hugo Hammars fond för sjöfartsteknisk forskning are also acknowledged for funding this research project.
7 References


Through our international collaboration programmes with academia, industry, and the public sector, we ensure the competitiveness of the Swedish business community on an international level and contribute to a sustainable society. Our 2,800 employees support and promote all manner of innovative processes, and our roughly 100 testbeds and demonstration facilities are instrumental in developing the future-proofing of products, technologies, and services. RISE Research Institutes of Sweden is fully owned by the Swedish state.

I internationell samverkan med akademi, näringsliv och offentlig sektor bidrar vi till ett konkurrenskraftigt näringsliv och ett hållbart samhälle. RISE 2 800 medarbetare driver och stöder alla typer av innovationsprocesser. Vi erbjuder ett 100-tal test- och demonstrationsmiljöer för framtidssäkra produkter, tekniker och tjänster. RISE Research Institutes of Sweden ägs av svenska staten.