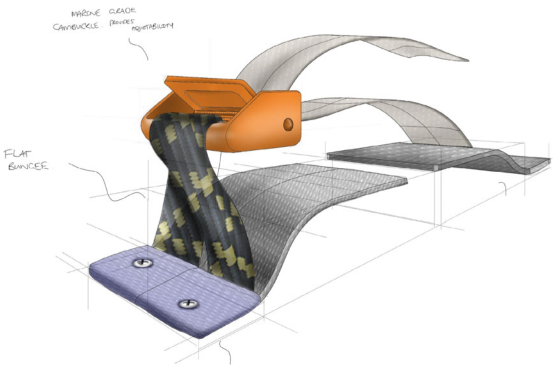
# Biomechanics and user testing of the impact of IRB modifications on tibial loading: Technical Report #8 to Surf Life Saving New Zealand (SLSNZ)

**By research team members for**
**TE HOKAI TAPUWAE – REIMAGINING SPORTS INJURY PREVENTION**

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This report is part of a series of technical reports for the research collaboration between Surf Life Saving New Zealand (SLSNZ) and AUT Sports Performance Research Institute New Zealand (SPRINZ).

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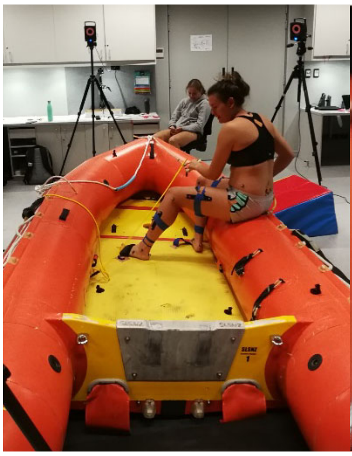
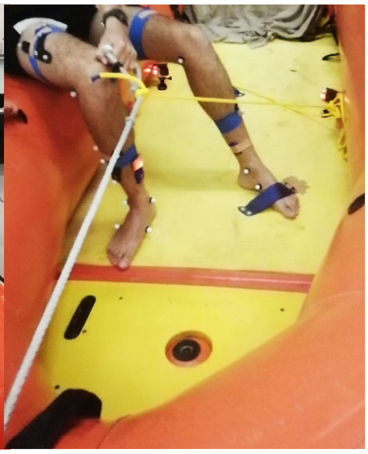
# Surf Life Saving New Zealand biomechanics and user testing of IRB impacts and body movements - Fact Sheet

## In-laboratory


Data:

- 3D motion capture
- IMUs
- Go Pros





Testing conditions:

- Foot straps – left + left & right
- Bow ropes – standard, additional attachment (yellow) + alternative (white with blue grip)
- Right hand grip – white rope (top of pontoon) + black handle (inside pontoon)

Analyses:

- 3D knee and ankle angles
- Left and right tibia loading

## On-water

| Standard IRB Standard foot straps | Standard IRB AUT foot straps | Prototype air hull IRB Standard foot straps |
|---|---|---|
|  |  |  |

AUT foot strap:

- Adjustable
- Bungee

Alternative bow rope:

- Adjustable
- 2 attachment points
- Movable handle

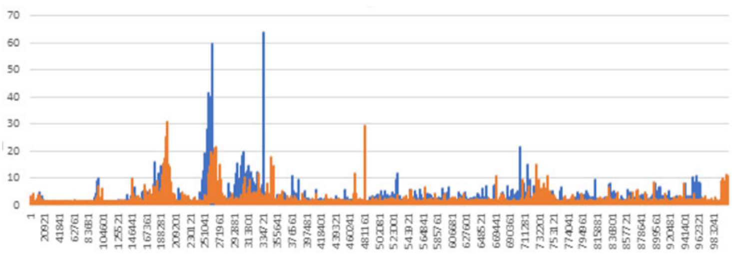
Testing conditions:

- Foot straps – standard + AUT
- Bow ropes – standard + alternative (white with blue grip)
- IRBs – standard + prototype air hull

Analysis:

Peak loading ($n$ = 3) during each trial ($n$ = 2) within each condition ($n$ = 6)

*Note: graph below is an example of right and left tibia acceleration data for one participant*




## Key Findings

- Lower limb loading during on-water testing was more than double in-lab testing
- Initial findings support the use of a modified foot strap
- Initial findings support using just the left foot strap compared to right and left foot straps together
- The prototype air hull IRB reduced lower limb loading to the greatest extent of the boats trialled, however the operational speed of the boat was reduced given the unfamiliarity by the crew driving
- Further investigation of AUT foot straps with the prototype air hull IRB is warranted given the results

## SUMMARY

**Background:** While driving and crewing an inflatable rescue boat (IRB), minimizing injury risk is of greatest priority. Foot straps bow ropes and hull characteristics are three key features which, through modification, may reduce current concern for lower limb injury to surf lifesavers. There is little quantified evidence of lower limb placement and motion or loading during surf lifesaving available within previous literature; only two studies have investigated loads experienced on IRBs during operation.

**Purpose:** To conduct biomechanics and user testing of the impact of IRB modifications of foot strap, bow rope and boat floor design on lower limb placement and tibial loading. Specifically, to investigate the influence of IRB modifications to lower limb kinematics and loading in-lab and on-water.

**Study approach:** The co-creation approach included multiple discussions with lifeguards, SLSNZ staff responsible for improving safety for lifeguards, boat designers, and the design and biomechanics academics. An iterative design and biomechanics lab testing approach was undertaken. The laboratory and on-water parts to the study were designed to provide biomechanics and user testing of the IRB modifications on the crew and driver lower limb positions and tibia impact loads.

**Methods:** Four experienced surf lifesavers took part in both in-lab and on-water phases of the study. **In-lab testing:** 3D motion capture of the left lower limb and acceleration data from two IMUs, one on each tibia. Three trials in 12 conditions were undertaken, consisting of foot strap, handle and bow rope combinations: A) left foot strap or both foot straps, B) right hand holding the white rope or the black handle, and C) standard, attached or alternative bow rope. The participants used momentum and grip with their right hand to lift the IRB, releasing at the top of the lift to emulate the impacts experienced as a crew member when going over a wave. Left leg knee and ankle angles, in addition to left and right tibia loading and limb asymmetries were calculated at the point of maximum impact. Each participant was asked a series of questions related to their IRB experiences. **On-water testing:** The four participants formed two pairings – females and males. One member of each pairing took the role of the driver and one was crew. Left and right tibia IMU units were affixed to each participant on each tibia and on their pelvis. In addition, two Go Pros were mounted to each IRB. Acceleration and video data were collected across six configurations of IRB (standard and prototype air hull), foot straps (standard and AUT modified) and bow rope (standard and alternative). Within each condition, two trials were performed, consisting of the participants entering the IRB, driving out as far as they felt comfortable, performing an open water turn, returning to shallow water, repeating and then exiting the IRB onto the shore. The Sunset beach surf conditions were moderate-to-large for the waves that were crossed. Resultant acceleration data were analysed for the three greatest impacts experienced by each participant within each trial. All data were analysed across all participants for each condition.

**Results: In-lab testing:** Analysis of tibial loading during landing showed the use of the left foot strap only had the greatest reduction in left tibia loading. Kinematic data indicated that reduced loading may be achieved through increased knee flexion, ankle dorsiflexion and reduced knee adduction. The maximum mean peak resultant acceleration was 27.7g. From the interviews, key themes were developed which identified the conditions for highest risk to include driver-error and over/under confidence of the crew. **On-water testing:** The considerable amount of tibial loading was greatest for the crew members and at the right tibia. The lowest loads were for the prototype air hull IRB with a standard left foot strap and the alternative bow rope. The maximum mean peak resultant acceleration was 76g. **Male versus female differences:** The higher loads for the males versus the females when controlled for body weight, were likely due to the observed faster velocities of the male crew in undertaking the on-water trials. There were no differences in the laboratory loads between the males and females when body weight was controlled for.

**Conclusions:** Tibial loading was high for crew members at their right tibia. Kinematic data analysis provided evidence to underpin the reduced loading when using the left foot strap only. The study provided insight into potentially beneficial ways in which current IRBs can be modified to reduce injury risk factors at the lower limbs. Initial support was provided for modifications of the foot strap and the modified IRB hull. Future research should investigate the potential injury implications of combining modified foot straps with IRB qualities, such as the incorporation of air cushioning in the hull. Focus should be placed on the reduction of loading of the crew and within the right tibia. Future work on modifications to the bow rope and handles are needed to enable participant selected lengths whilst including three-point loading for stability. Additional investigation into on water driver behavior is warranted to further understand the role of behavior in injury risk.

## INTRODUCTION

Surf Lifesaving New Zealand (SLSNZ) is responsible for the coordination and oversight of lifeguard certifications, equipment standards, and member training across NZ, therefore safety and injury prevention are paramount. To enhance safety of the driver and crew, each IRB is fitted with foot straps and a bow rope for the crew member to hold on to. Using these features, the crew member is responsible for keeping the IRB balanced through the surf, requiring regular movement of their whole body. The driver is responsible for navigating the IRB through the surf as efficiently as possible while ensuring the crews' safety.

### BODY LOADS DURING SURF LIFESAVING IN IRBS

Driving an IRB through surf can require a substantial physical effort which likely places considerable loading on the body. However, only two studies have investigated loads experienced on IRBs during operation. Yorkston et al. (2005) utilized a custom-built piezo-electric strain gauge to assess forces experienced at the foot straps during on-water boat operation, in addition to one on-board video recorder to assess crewing technique. Results from trials using a typical range of IRB operation techniques during a 10 minute period of a sub-sample from 15 crew indicated that the crew members' left foot was experiencing the greater amount of load (peak force: 415.6N), compared to the right foot (peak force: 252.9N → 25.8g). Note: by dividing data in "N" by 9.81, outputs are converted to "g" units.

### THE RELATIONSHIP BETWEEN LOWER LIMB LOADING, BODY MOTION AND INJURY

The foot and shank segments which from the ankle joint encompass a complex formation of anatomical structures. The interplay between body positioning of these structures and the forces applied underpin the risk of injury. As is demonstrated in Figure 1, there are many elements of the ankle which are susceptible to injury, given a specific set of circumstances. The amount of loading that can be endured by the joint, before injury occurs, is task and individual-dependent, however, the greater the load endured, the greater the risk of injury (Solligard et al., 2016).

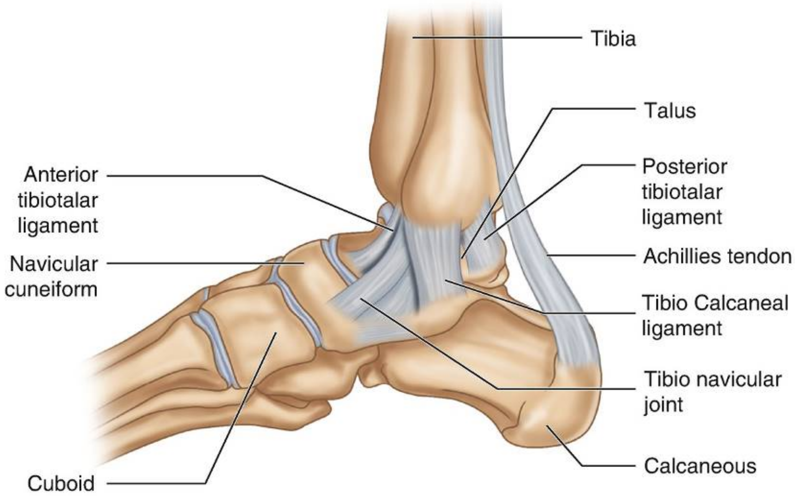



**Figure 1. Images of ankle joint anatomy.**

Within surf lifesaving, greater left side loading (~42.4g) was found, compared to the right side (~25.8g) by Yorkston et al. (2005). However, several epidemiological studies have indicated a greater number of injuries to the right foot (Bigby et al., 2000; Mitchell et al., 2013). This finding warrants the need for not only further investigation of loading experienced, but also of body motion and foot placement during high loading.

The magnitude of accelerations could be a major influence in the cause of impact injuries to surf lifesavers, particularly with the repetitive nature of IRB operation (Ludcke et al., 2001). There is currently no quantified evidence of the impact of routine maneuvers performed by driver and crew in IRBs on lower limb mechanics.

### BOAT DESIGN IMPLICATIONS FOR INJURY

Insight into the technique used by surf lifesavers at the point of peak impact during training and rescue is anticipated to expose areas of concern in the way of injury risk factors and will therefore be of value to drive further research and initiatives to injury risk reduction. Modifications to standard IRBs may be beneficial in reducing loading experience by both drivers and crew.

The right foot strap design has been identified as a potential issue related to lower limb injury prevalence (Ashton and Grujic, 2001; Ludcke, 2001) and therefore has been removed in many IRBs, leaving the crew member with only the left foot strap.

The standard foot strap design is currently fixed and therefore cannot be adapted based on foot size. In addition, the material used has little give and may therefore contribute to the forces experienced at the lower limbs by acting as a rigid mass which the foot may impact against. The current bow rope design is affixed to the IRB at one point and is not easily modifiable for arm length or reach. These are two features may impact loading of the lower limbs therefore their potential for modification should therefore be explored.

**STUDY PURPOSE**
The purpose of this study was to conduct biomechanics and user testing of the impact of IRB modifications of foot strap, bow rope and boat floor design on lower limb placement and tibial loading. Specifically, we aimed to investigate lower limb angles and lower limb loading at the point of boat impact because of IRB modifications in-lab and on-water.

**STUDY APPROACH**
The co-creation approach included multiple discussions with lifeguards, SLSNZ staff responsible for improving safety for life guards, boat designers, and the design and biomechanics academics (Figure 2). An iterative design and biomechanics lab testing approach was undertaken. The laboratory and on-water parts to the study were designed to provide biomechanics and user testing of the IRB modifications on the crew and driver lower limb positions and tibia impact loads.


**Figure 2. A co-creation approach involving surf lifeguards, surf life administrators, boat designers and academics in design and biomechanics was taken to address the study questions.**

## PART I. FOOT STRAP DESIGN AND PROTOTYPE IN-LAB TESTING

**STANDARD IRB COMPONENTS**
The IRBs consist of six key potentially modifiable components: hull, bow rope, foot strap, EVA deck, stern handle and bow handle. Although there are opportunities for redesign of each of the identified components, the foot strap was considered as a priority due to its association with ankle injuries and abrasion.

**Standard foot strap design:** There are three main factors determining the design: 1) level of adjustability; 2) comfort; 3) minimizing risk of foot strap being a hazard. The existing design is prone to inversion ankle rolls, sprains and breaks as it essentially traps the ankle. Most of the foot straps are made from polywebbing with a neoprene layer. Neoprene help to reduce abrasions; however, it does degrade. Both the polywebbing on the strap and its attachment to the floorboard have been reported to causes abrasions to the crew member’s feet.

**RE-DESIGNING IRB FOOT STRAP**

Different foot strap concepts were trialed, including buckles, bungees (Figure 3) and sleeve materials (Figure 4).


**Figure 3. Images of the final functional protype foot strap design.**

Various concepts were explored, including buckles and bungees. The final functional prototype was designed to include a one-sided flat cambuckle with a long strap affixed on the opposite side and a flat bungee. The bungee has been designed to allow for increased ankle range of motion, in comparison with the standard foot strap. The buckle allows the strap to be easily adjusted for different foot sizes and is made with zinc alloy to prevent corrosion from UVA and salt.

**Figure 4. Image of the sleeve designed to cover the buckle and bungees of the foot strap.**

To ensure optimal comfort and safety of the foot strap, it was vital to completely cover the components to reduce the risk of potential hazards, including toe de-gloving and abrasion. A red ring was screen printed to the neoprene material to indicate to the user where the cambuckle is located under the sleeve, enabling quick access.

## PART II. IN-LAB TESTING

**METHODS**

Ethics approval for the study was gained from Auckland University of Technology Ethics Committee (AUTEC # 18/380).

***Participants***

Four experienced surf lifesavers

Table 1), 2 male and 2 female, attended the in-lab biomechanics testing that included a standard IRB boat surrounded by high speed motion cameras (Figure 5). Each participant was recruited through SLSNZ and had experience with surf lifesaving from a young age.

**Table 1. Participant demographics.**

| Participant | P1 | P2 | P3 | P4 |
|---|---|---|---|---|
| Age (years) | 26 | 27 | 21 | 23 |
| Height (cm) | 192.9 | 192.7 | 174.0 | 179.7 |
| Mass (kg) | 96.6 | 91.6 | 72.1 | 75.0 |

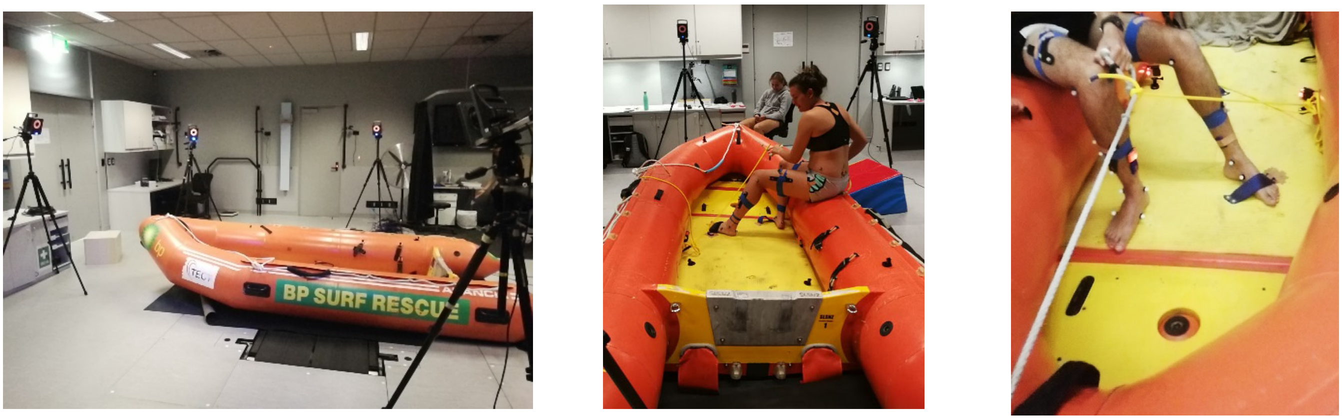



**Figure 5. The in-lab biomechanics testing that included a standard IRB boat surrounded by high speed motion cameras.**

***Protocol***

The participants were provided with an explanation of the plan for the data collection, following which they provided informed consent and completed a general health questionnaire. Mass and height were measured and recorded. Participants were then marked up with Vicon reflective markers and IMU sensors before beginning the trials. They were asked to wear shorts and no shoes, no shirt for the males and a sports bra for the females.

Data collection consisted of three static trials, a functional squat and functional hip motion series for each leg. Each participant was asked to sit as they would if they were crewing the IRB and perform the same movements under different conditions. The motion was described as attempting to simulate the IRB lifting over a wave and dropping following the wave. The participants were shown a recorded demonstration of the maneuver in the lab and given as much time to practice the maneuver as they wished. Once they were happy to start data collection, they began with the first condition, which they performed three trials of, followed by a rest period long enough to feel ready to perform the next trial to full effort.

During their time in the biomechanics laboratory, participants engaged in short interviews, intended to be open-ended though which understanding of the participant's experience using IRBs would be gained.

***Data collection***
Markers were positioned on the left and right of the following anatomical locations: anterior superior iliac spinae, posterior superior iliac spinae, iliac crest, thigh (cluster), lateral condyle, medial condyle, shank, lateral malleolus, medial malleolus, calcaneus, lateral midfoot, medial midfoot, 5$^{th}$ metatarsal, 1$^{st}$ metatarsal (Figure 6). Inertial units were affixed to the right and left tibia using double-sided tape and secured with medical tape. Once marked up, IMU sensors were connected to the iCaptureU software.

The bow rope designs which were tested included will be referred to as a) standard, b) additional attachment and c) alternative. Each of these rope configurations can be seen in Figure 7. The additional attachment rope was a modification of the standard bow rope with an added point of contact to increase the stability of the crew person. The alternative bow rope is attached along the left of the IRB. The purpose of the alternative configuration was again, to increase support and stability. Each of the modified bow rope configurations (additional attachment and alternative) were modified according to participants' reach (arm length) and comfort.

Each trial was initiated by a countdown from three. The conditions (Figure 7) consisted of combinations of a standard, additional attachment and alternative bow rope with either a black or white handle and either a left foot strap or left and right foot straps:

1) standard bow rope, black handle, left foot strap.
2) standard bow rope, white handle, left foot strap.
3) additional attachment bow rope, black handle, left foot strap.
4) additional attachment bow rope, white handle, left foot strap.
5) alternative bow rope, black handle, left foot strap.
6) alternative bow rope, black handle, left foot strap.
7) standard bow rope, black handle, left and right foot straps.
8) standard bow rope, white handle, left and right foot straps.
9) additional attachment bow rope, black handle, left and right foot straps.
10) additional attachment bow rope, white handle, left and right foot straps.
11) alternative bow rope, black handle, left and right foot straps.
12) alternative bow rope, black handle, left and right foot straps.

**Figure 6. Participant mark up with 3D markers and IMUs.**


a-c)


d)


e)

**Figure 7. The conditions consisted of combinations of a standard bow rope (a), an additional attachment bow rope, or an alternative bow rope (a-c) with the right hand gripping a white handle (d) or a black handle (e).**

During the interviews, audio recording was taken while the interviewer worked through a series of questions related to IRB practice. The questions asked were:

1. Can you describe a time when you felt really safe in a rescue/racing IRB? What are all the different factors that contributed to this? (what did you notice, what did you hear, what did you feel?)
2. Can you tell us some of the experiences that you have had where you have felt unsafe when in a RIB boat? What are all the different factors that contributed to this?
3. Describe those activities most high risk? What makes these risky?
4. Have you been injured while using an IRB? What factors contributed to you being injured?

5. How does your sense of safety change with different boat drivers?
6. What makes rescues/racing dangerous or risky (for the boat crew)?
7. How would you describe the culture around health and safety in your club and the broader organization? How does the culture of health and safety influence crew and driver behaviour?
8. Who is responsible for the safety of the rescue boat team during a rescue and how does this influence behavior?

***Data analyses***

Three-dimensional motion capture data from the left leg was gap-filled and analysed using Nexus and Visual3D software before being exported to Excel, along with inertial sensor data. Kinematic and IMU data were synchronized from using the greatest vertical displacement in the left tibia positional data and the greatest vertical impact in the IMU z data; the point at which the IRB began accelerating towards the ground was used as the starting point. Due to different sampling rates, MATLAB® was used to interpolate the kinematic data, allowing frame-by-frame comparison between the kinematic and IMU data. Once this was complete, knee and ankle angles, peak loading for each limb and limb asymmetries were analysed in each condition at the point of maximum impact.

Resultant tibial acceleration can be calculated from all axes of a tri-axial accelerometer to provide a single metric that is independent of the sensor orientation. Resultant tibial acceleration is a surrogate measure for impact loading. Raw IMU acceleration data from each direction (x,y,z or medio-lateral, anterio-posterior, vertical) informed the calculation of resultant acceleration using the following equation:

$$a_r = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

where $a_r$ is the resultant acceleration, $a_x$ is the acceleration is the x-direction, $a_y$ is the acceleration in the y-direction and $a_z$ is the acceleration in the z-direction. All accelerations are expressed in gravitational units (g) (1g (gravitational unit) is equal to the gravitational acceleration of 9.81 m/s$^2$).

Interview data were interpreted using a thematic analysis approach to identify general trends in the answers that the participants gave. This approach allows for important aspects of the responses to given to all questions to be drawn out. Thereby providing condense outputs which are useful for recommendations, rather than extensive text.

**RESULTS**

***Interview data***

From the interviews, key themes were identified from the interview data were:

1. Unsafe practice factors:
    1. driver actions (unnecessary - fast, erratic, reckless)
    2. comfort with the surf conditions
    3. number of people in the IRB (multi-patient pick-up)
    4. other people's opinions
    5. different beaches (not own)
2. Conditions for highest risk of injury:
    1. driver error
    2. over-confidence/under-confident (panic)
3. Different drivers have a huge effect on perceived safety
4. Emphasis on health and safety varies between clubs
5. Woman appear to be more aware of a sense of judgement with respect to making errors or their ability.

***Tibial loading***

Analysis of tibial loading during landing showed left foot strap only to have the greatest reduction in left tibia loading (Figure 8). The finding was consistent across participants. Greatest overall impacts occurred using the alternative bow rope. This condition was unfamiliar to the participants and was conducted later in the testing session which may have affected results. Most participants, other than P3, experienced greater impacts through their right tibia (Table 2), reaching an excess of 5g in some trials. Highest mean peak loading was experienced by P1 (>20g).

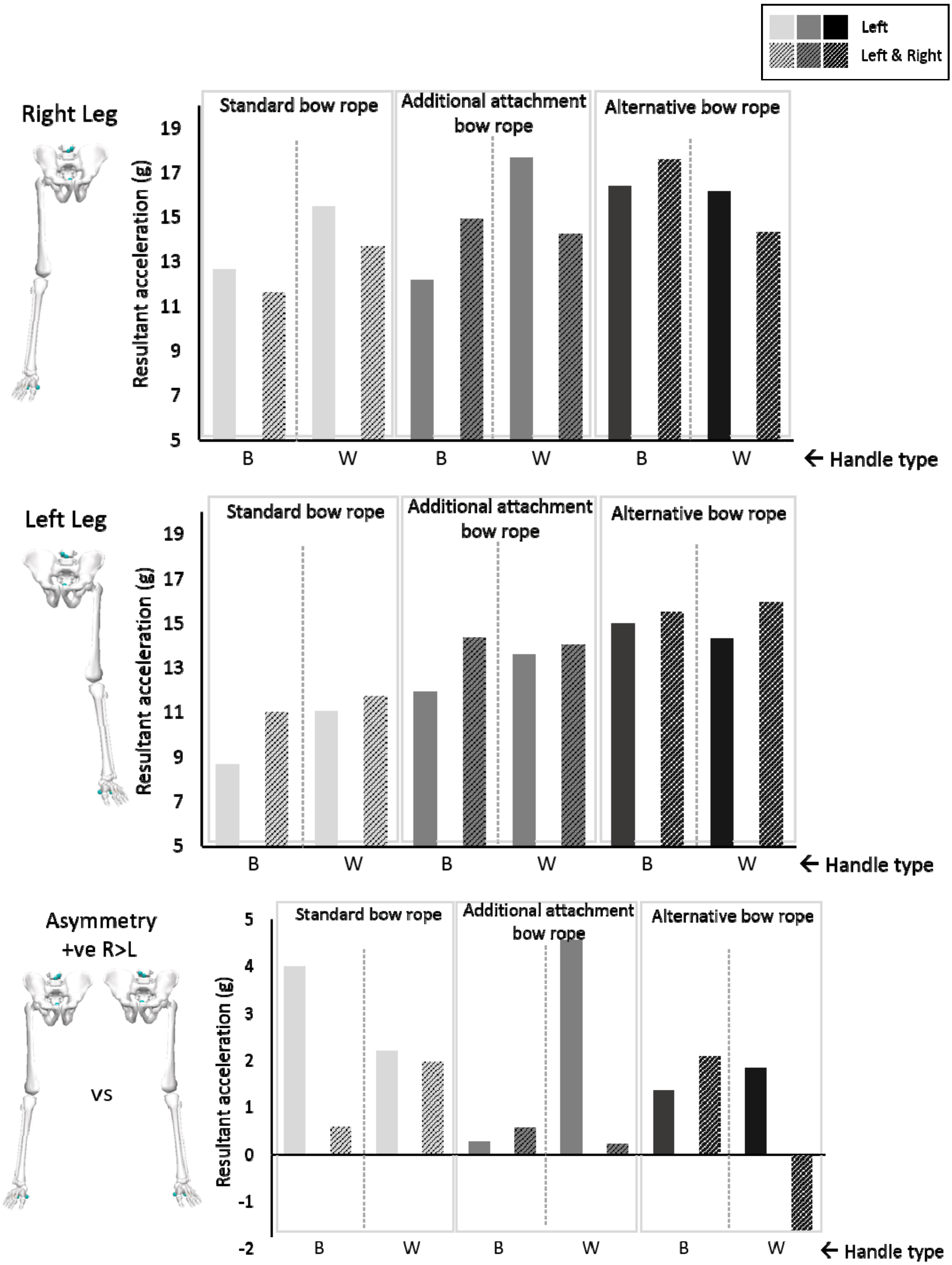



**Figure 8. Mean participant in-lab loading values (g) for right tibia, left tibia and the difference between right and left (asymmetry) under each of the 12 conditions where B = black IRB handle and W = white IRB rope.**

**Table 2. Mean loading experienced across trials for each limb and a comparison between limbs.**

| | | Standard bow rope | | Standard bow rope | | Additional attachment bow rope | | Additional attachment bow rope | | Alternative bow rope | | Alternative bow rope | | Mean loading |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Tibia IMUs | B-L | B-LR | W-L | W-LR | B-L | B-LR | W-L | W-LR | B-L | B-LR | W-L | W-LR | |
| P1 | RTB | 16.4 | 15.1 | 24.1 | 21.3 | 22.4 | 21.7 | 27.7 | 22.3 | 26.8 | 26.8 | 26.7 | 25.7 | 23.1 |
| | LTB | 12.8 | 12.3 | 16.0 | 17.4 | 19.2 | 24.6 | 24.0 | 20.8 | 25.1 | 23.0 | 24.3 | 26.2 | 20.5 |
| | RTB v LTB | 3.6 | 2.8 | -0.8 | 4.0 | 3.2 | -2.9 | 3.7 | 1.4 | 1.8 | 3.9 | 2.4 | -0.5 | 1.9 |
| P2 | RTB | 19.5 | 19.0 | 24.3 | 21.7 | 15.8 | 18.6 | 19.6 | 19.8 | 22.6 | 21.8 | 18.4 | 18.0 | 19.9 |
| | LTB | 12.0 | 17.4 | 17.9 | 15.2 | 12.8 | 14.2 | 15.3 | 17.2 | 20.3 | 20.7 | 19.2 | 21.0 | 16.9 |
| | RTB v LTB | **7.4** | 1.6 | **6.5** | **6.5** | 3.0 | 4.4 | **6.3** | 2.6 | 2.3 | 1.1 | -0.8 | -3.0 | 3.2 |
| P3 | RTB | 5.4 | 3.5 | 3.5 | 4.0 | 4.5 | 4.5 | 9.4 | 4.6 | 4.2 | 7.2 | 5.7 | 6.1 | 5.2 |
| | LTB | 6.3 | 5.4 | 5.4 | 4.1 | 8.0 | 5.0 | 7.1 | 8.3 | 5.7 | 6.2 | 4.3 | 8.2 | 6.2 |
| | RTB v LTB | -0.9 | -1.8 | -1.9 | -0.2 | -3.5 | -0.5 | 2.3 | -3.7 | -1.6 | 1.0 | 1.4 | -2.0 | -0.9 |
| P4 | RTB | 9.4 | 8.8 | 10.1 | 7.9 | 6.1 | 15.0 | 14.0 | 10.4 | 12.0 | 14.6 | 14.0 | 7.6 | 10.8 |
| | LTB | 3.5 | 9.0 | 4.9 | 10.3 | 7.7 | 13.7 | 8.0 | 9.8 | 8.9 | 12.2 | 9.5 | 8.5 | 8.8 |
| | RTB v LTB | **6.0** | -0.2 | **5.1** | -2.4 | -1.6 | 1.3 | **6.0** | 0.6 | 3.0 | 2.4 | 4.5 | -0.9 | 2.0 |

*All units: g; B – black handle; W – white rope; L – left foot strap; L&R – left and right foot straps; RTB right tibia, LTB left tibia*

*Highlighted >20g for males (P1&P2); highlighted >10g for females (P3&P4); Values in* ***bold****: asymmetry >5g*

*Kinematic data*

When maximum tibial loading was experienced, all participants were in a position of ankle dorsiflexion, abduction and inversion (Figure 9, Table 3) and knee flexion, adduction and internal rotation (Figure 10, Table 4). Conditions with only the left strap showed decreased knee adduction, with the greatest knee flexion. Ankle dorsiflexion and inversion were additionally greatest in the condition with left foot strap only.

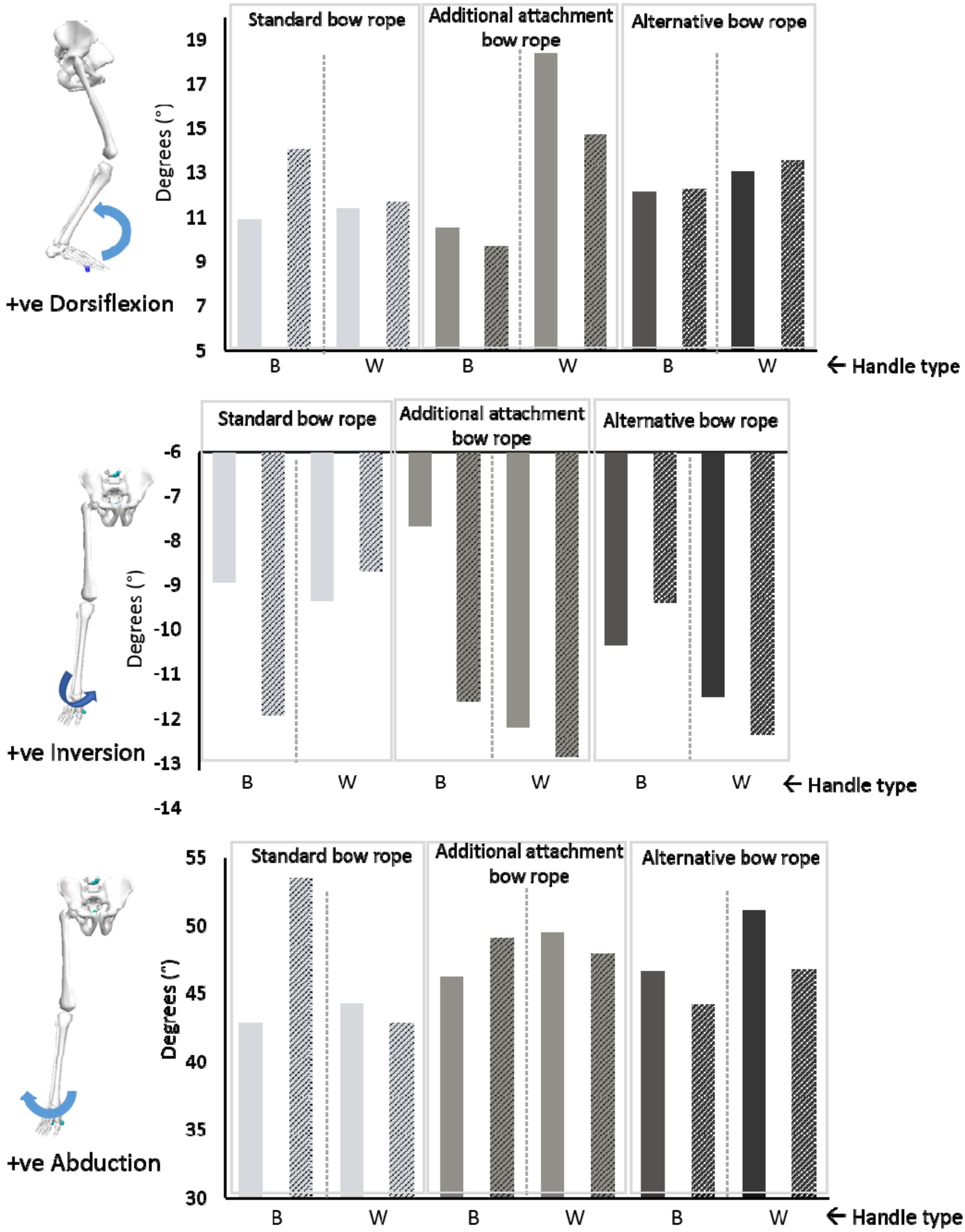



**Figure 9. Mean participant in-lab kinematic data outputs (⁰) for left ankle angles at the point of maximum loading**

during each of the 12 conditions.

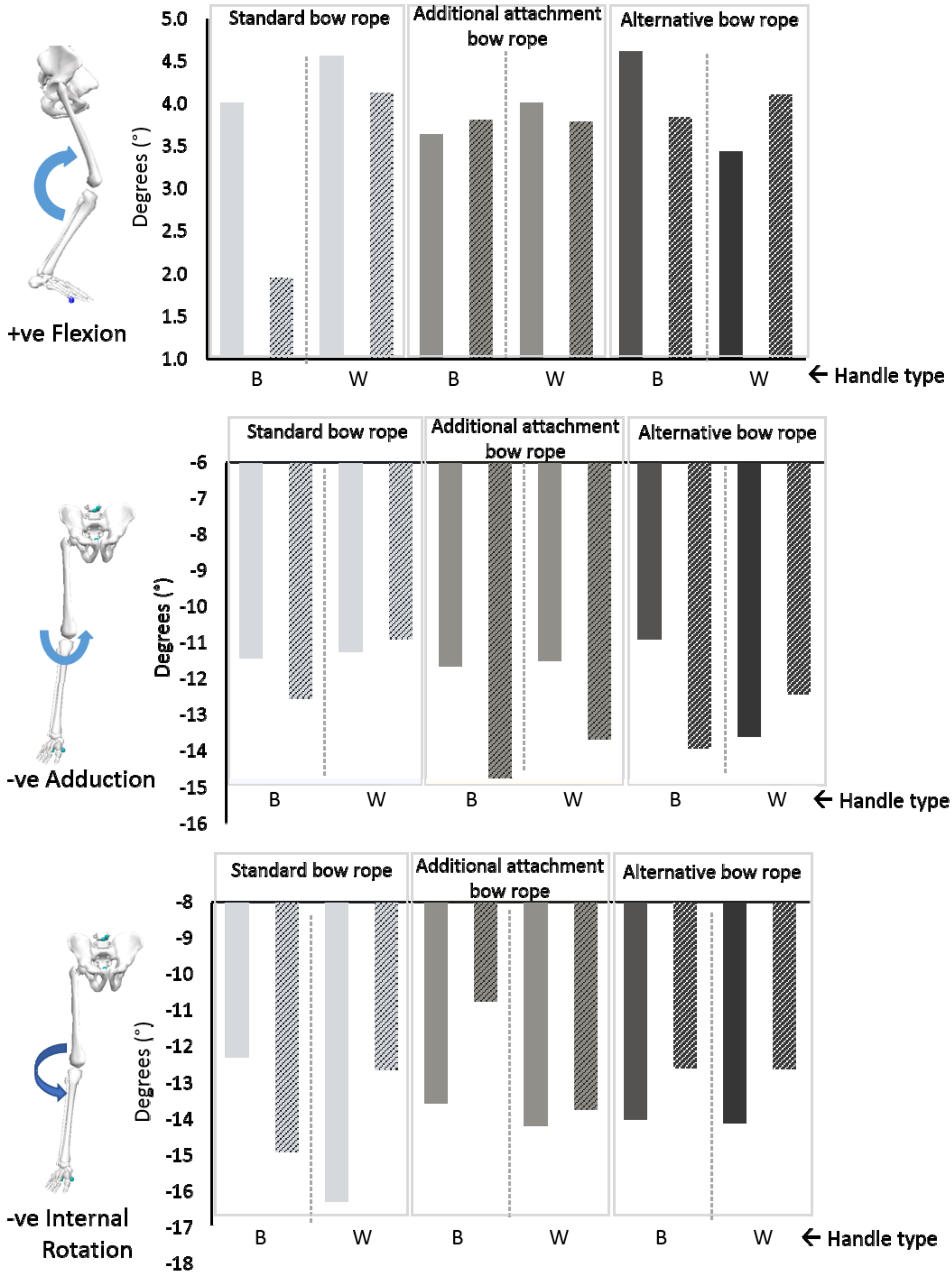



**Figure 10. Mean participant in-lab kinematic data outputs ($^{o}$) for left knee angles at the point of maximum loading during each of the 12 conditions: where B = black IRB handle and W = white IRB rope.**

**Table 3. Mean ankle angles at the point of greatest load experienced across trials for each participant in each condition.**

| | | Standard bow rope | | Standard bow rope | | Additional attachment bow rope | | Additional attachment bow rope | | Alternative bow rope | | Alternative bow rope | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | B-L | B-LR | W-L | W-LR | B-L | B-LR | W-L | W-LR | B-L | B-LR | W-L | W-LR |
| P1 | Ankle x | 15.84 | 14.02 | 13.25 | 14.75 | 33.27 | 10.29 | 13.43 | 9.22 | 13.95 | 14.46 | 16.14 | 17.90 |
| | Ankle y | 48.45 | 49.27 | 44.65 | 42.98 | 46.82 | 41.95 | 41.66 | 53.09 | 50.66 | 42.78 | 57.65 | 60.60 |
| | Ankle z | -11.90 | -10.82 | -9.45 | -8.22 | -16.63 | -7.56 | -8.75 | -8.93 | -10.71 | -9.02 | -14.45 | -16.42 |
| P2 | Ankle x | 6.98 | 6.73 | 8.94 | 8.07 | 16.89 | 18.56 | 6.62 | 9.55 | 4.71 | 13.91 | 9.38 | 10.22 |
| | Ankle y | 59.00 | 64.01 | 57.22 | 64.96 | 79.12 | 72.41 | 73.14 | 71.50 | 54.99 | 64.95 | 69.83 | 58.34 |
| | Ankle z | -12.40 | -13.71 | -14.66 | -14.74 | -19.80 | -23.00 | -10.54 | -23.97 | -12.31 | -14.74 | -15.97 | -16.01 |
| P3 | Ankle x | 11.60 | 23.86 | 11.06 | 14.45 | 13.81 | 10.50 | 11.03 | 10.62 | 14.46 | 11.12 | 16.47 | 13.24 |
| | Ankle y | 34.11 | 62.33 | 33.78 | 31.26 | 35.03 | 33.92 | 34.26 | 32.73 | 32.15 | 36.17 | 35.77 | 34.60 |
| | Ankle z | -3.38 | -13.36 | -3.70 | -2.96 | -3.53 | -4.26 | -3.31 | -3.22 | -5.02 | -3.39 | -5.68 | -5.54 |
| P4 | Ankle x | 9.28 | 11.69 | 12.41 | 9.61 | 9.61 | 19.63 | 11.07 | 9.34 | 15.46 | 9.60 | 10.27 | 12.92 |
| | Ankle y | 29.69 | 38.45 | 41.60 | 32.26 | 37.13 | 43.51 | 36.08 | 39.35 | 49.08 | 32.94 | 41.37 | 33.67 |
| | Ankle z | -8.04 | -9.80 | -9.59 | -8.74 | -8.76 | -16.55 | -7.98 | -10.28 | -13.34 | -10.38 | -9.89 | -11.39 |

*All units: degrees ($^o$); BLK – black handle; WT – white rope; L – left foot strap; L&R – left and right foot straps*

**Table 4. Mean knee angles at the point of greatest load experienced across trials for each participant in each condition.**

| | | Standard bow rope | | Standard bow rope | | Additional attachment bow rope | | Additional attachment bow rope | | Alternative bow rope | | Alternative bow rope | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | B-L | B-LR | W-L | W-LR | B-L | B-LR | W-L | W-LR | B-L | B-LR | W-L | W-LR |
| P1 | Knee x | 7.52 | 7.91 | 7.75 | 7.77 | 7.83 | 8.12 | 7.31 | 7.09 | 9.25 | 7.86 | 8.14 | 7.71 |
| | Knee y | -9.11 | -4.27 | -6.31 | -6.35 | -5.84 | -5.61 | -7.11 | -13.45 | -3.98 | -4.68 | -5.82 | -6.58 |
| | Knee z | -10.32 | -9.72 | -12.05 | -11.81 | -8.75 | -8.76 | -9.83 | -5.13 | -16.53 | -10.93 | -13.99 | -11.00 |
| P2 | Knee x | 7.36 | 5.09 | 8.76 | 8.40 | 8.17 | 8.78 | 7.53 | 9.11 | 7.84 | 9.03 | 7.16 | 8.53 |
| | Knee y | -19.97 | -16.56 | -16.57 | -20.71 | -20.67 | -19.12 | -18.84 | -25.22 | -17.25 | -26.83 | -24.02 | -22.34 |
| | Knee z | 1.53 | -6.71 | -7.23 | -0.01 | -4.65 | -7.28 | -2.42 | -0.59 | -1.33 | 3.02 | -1.57 | -0.85 |
| P3 | Knee x | 4.23 | -2.15 | 5.25 | 2.34 | 3.72 | 2.45 | 2.92 | 2.11 | 5.66 | 1.44 | 2.01 | 2.79 |
| | Knee y | -0.57 | -10.75 | 1.00 | -3.25 | -1.64 | -2.95 | -2.10 | -4.15 | 1.90 | -4.57 | -3.48 | -1.30 |
| | Knee z | -26.62 | -31.19 | -30.28 | -25.26 | -27.97 | -26.87 | -26.02 | -24.04 | -29.21 | -27.89 | -24.12 | -27.51 |
| P4 | Knee x | -3.07 | -3.03 | -3.51 | -1.98 | -3.67 | -4.21 | -3.19 | -3.05 | -4.26 | -2.94 | -3.55 | -2.62 |
| | Knee y | -16.01 | -18.53 | -23.13 | -13.27 | -17.82 | -26.92 | -18.49 | -18.73 | -24.27 | -19.59 | -21.05 | -19.39 |
| | Knee z | -13.70 | -11.99 | -15.55 | -13.45 | -15.37 | -12.05 | -15.97 | -13.16 | -8.91 | -14.57 | -16.68 | -11.03 |

*All units: degrees ($^o$); B – black handle; W – white rope; L – left foot strap; L&R – left and right foot straps*

## PART III. ON-WATER TESTING

**METHODS**
***Participants***
As with the in-lab testing, four experienced surf lifesavers (two females and two males, Table 1) took part in the on-water data collection. One of each pairing (one female and one male) took on the role of the crew member and the other, the role of the driver. All participants were able to undertake their preferred roles. Written informed consent was obtained from all participants, in addition to a general health survey.

***Protocol***
All participants were briefed on the collection requirements and their roles. Each participant was then fitted with two IMU units, one located on each tibia (right and left limb, Figure 11). The waterproof IMU units were secured to each participant with tape (see equipment list in Table 5). The participants were then given ample time to warm up in whatever way they felt was most appropriate.


**Figure 11. Locations of IMU sensors on both crew member and driver on the prototype air hull IRB.**

Only the standard IRB hull was used in the in-lab testing. Two separate IRBs were included in the on-water testing, a standard hull and the prototype air hull. The primary design difference, for the purpose of this investigation, between the two was within the floorboard and floor layer. Whereas the standard IRB is fitted with a two-piece rigid floorboard which is hinged forward of the crew person's left foot strap, the prototype air hull IRB utilizes an inflatable floor layer, i.e. there is no rigid floor layer.

Within each of the six conditions (Table 6, Figure 12), the participants entered the IRB in shallow water, drove out as far as they felt comfortable, turned and came back to shallow water. This series of events was performed twice for each condition before participants exited the IRB (i.e. two trials per condition, Figure 13 and Figure 12). During each trial, participants navigated over between four and six waves of moderate (~1.5m) to large (~2.0m) sizes. Participants were able to rest as long as they wanted before moving on to the next condition.
The length of the alternative bow rope was decided upon through conversation between the SLSNZ National Powercraft Officer and each of the crew members; it therefore varied between the female and male participants. In addition, the AUT foot strap was adjusted to the participants' foot size and preference through conversation with the AUT design team.

**Figure 12. Illustration of the different types of IRBs and bow ropes (circled in far-right image). Left image: standard IRB, standard foot strap; middle image: standard IRB, modified foot strap; right image: prototype air hull IRB, standard foot strap.**

**Figure 13. Photographs demonstrating exit from standard IRB onto the shore.**

***Data collection***
Acceleration data were collected from four IMU devices affixed to the driver and crew member. Simultaneous video footage was captured using Go Pros mounted at the back left and right of the IRBs (Figure 14). GoPro positions were kept consistent between conditions and across participants.

**Table 5. Equipment used for data collection and analysis.**

| Equipment | Description of Use | Quantity Used |
|---|---|---|
| | **Hardware** | |
| Laptop | Laptops for inertial sensor synchronisation, data collection, and data storing | 2 |
| Inertial Measurement Unit / Sensor (IMU) | Blue trident IMeasureU sensors to capture acceleration data (z,y,z) at 1600Hz | 4 |
| Associated IMU Equipment | Blue trident bases to connect sensor to laptop | 4 |
| Phones | Mobile phones to record video footage from the shore | 2 |
| Double Sided Tape | Used to secure the IMUs to the participants | 1 Roll |
| Medical Tape (blue) | Used to secure the IMUs to the participants | 4 Rolls |
| Medical Tape (brown) | Used to secure the IMUs to the participants | 2 Rolls |
| GoPro | GoPro Hero 4 | 3 |
| GoPro Attachments | Flotations, mounts | 3 |
| Gaffer tape | Used to secure the GoPro mounts to the IRB | 1 |
| GoPro Memory Devices | SD cards | 3 |
| | **Software** | |
| iCaptureU | Inertial Sensor Software for synchronisation, data import, and analysis | - |
| Matlab 2018b (MathWorks) | Inertial data analysis | - |
| Microsoft Excel | Inertial data analysis | - |

Four waterproof 9-axis inertial measurement units (Blue trident, iMeasureU) were used for on-water collection. Each IMU sensor contained two 3-axis accelerometers (low ±16g, 1125Hz and high ±200g, 1600Hz), a gyroscope (±2000$^{o}$/s, 1125Hz) and a magnetometer (±4900uT, 200Hz).

The IMUs were attached on the crew's left and right tibia, and the driver's left and right tibia with double-sided tape and medical tape (blue then brown). Prior to each collection, each unit was configured using iCaptureU software. Each IMU sensor was then connected to the iPad software (iCaptureU) to allow data capture (Figure 15 and Figure 16). Following each trial, data capture was stopped.

**Figure 14. Go Pro locations throughout testing.**

**Figure 15. IMU sensors being connected to software on the iPad.**

In order to synchronise data on both the inertial sensor data and GoPro footage the crew member was instructed to stand in the centre of the floorboard inside the IRB, in view of all GoPro cameras, and to perform a jump.

***Data analyses***

Right and left tibia data (x,y,z) were extracted into Microsoft Exell worksheets and resultant (gravitational) acceleration data were calculated. Figure 16 shows an example of resultant acceleration data used to determine trials and impact events, where the orange trace is the RTB and the blue trace is the LTB.

Data were synchronized with video footage using the initial jump performed at the start of each condition. The start and end of each trial were identified, along with key events (i.e. impacts resulting from going over a wave confirmed by on-boat GoPro video and shore-based video).

The three most significant impacts from each trial were identified using peak resultant acceleration values. Peak data outputs were averaged across trials, providing an average peak load experienced per participant per condition. Data were then divided into driver and crew to investigate the influence of the differing surf lifesaving roles on tibial loading.

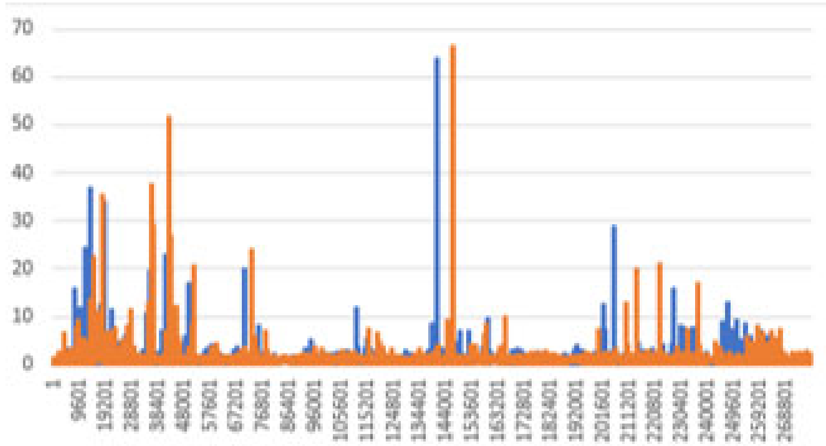



**Figure 16. An example of resultant acceleration data used to determine trials and impact events.**

**RESULTS**

***Tibial loading***

There was substantial mean peak resultant acceleration (g) with values of up to 53g (Table 6). Overall, lower limb loading was greater for crew than drivers (Figure 17). Crew members experienced an average peak loading of 30g across all conditions, while drivers experienced 23g. Although it differed between conditions, the overall average lower limb loading experienced by the drivers was consistent between limbs; however, crew members' right leg endured substantially greater tibial loading than the left (34g and 25g, respectively). Crew members experienced high lower limb loading during several trials which resulted in peak resultant acceleration values of >40g.
The IRB used had a substantial influence on the magnitude of loading experienced at the lower limbs. The lowest loading for both driver and crew was in the prototype air hull IRB, incorporative the alternative bow rope. The introduction of the modified AUT foot strap had little influence on the RTB but led to a reduction in loading of the left tibia, which was prominent when used in conjunction with the standard bow rope for the crew.

The influence of bow rope type is evident from Figure 17. As the bow rope had no direct influence on the drivers, there is little variation between loading experienced within each condition. However, the amount of right tibia loading was impacted by the introduction of the modified rope in each condition. When in the standard IRB, right tibia loading increased when the modified (alternative) bow rope was introduced, however, the same was not true when using the prototype air hull IRB.

Participant 1 experienced the greatest lower limb loading overall. The greatest average peak loading was 76g at the right tibia with a standard IRB, alternative bow rope and a standard foot strap (Table 6). Each of the participants generally experienced greater right tibia loading than left tibia, with few exceptions, other than participant 4 who experienced a mix of right and left dominant tibial loading.

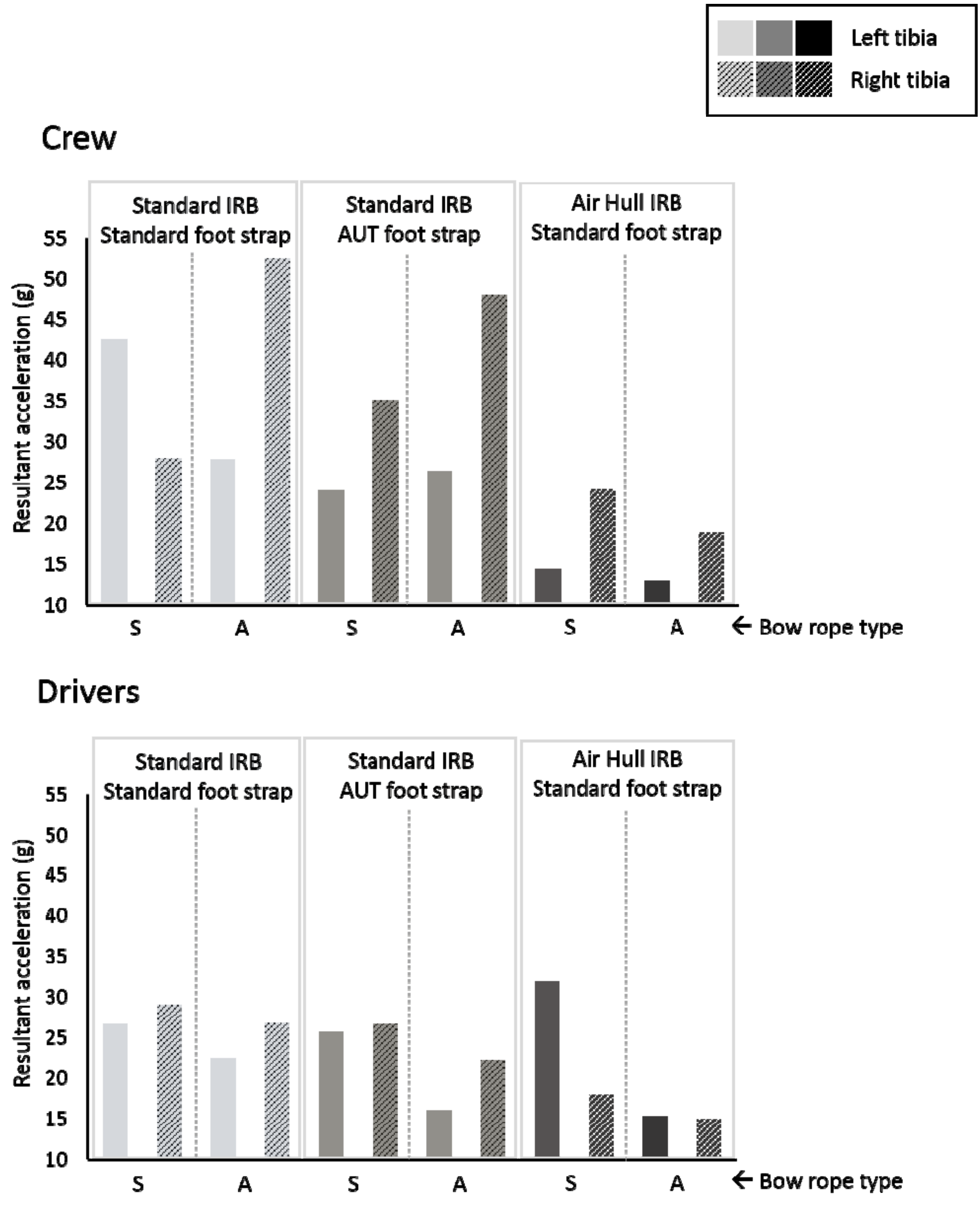



**Figure 17. Mean participant on-water loading values (g) for left tibia (LTB) and right tibia (RTB) under each of the six conditions including the standard bow rope (S) and alternative bow rope (A).**

**Table 6. Mean loading per participant experienced across trials for each limb, in addition to division into crew and driver.**

| | Standard IRB Standard bow rope Standard foot strap | | Standard IRB Alternative bow rope Standard foot strap | | Standard IRB Standard bow rope AUT foot strap | | Standard IRB Alternative bow rope AUT foot strap | | Prototype Air Hull IRB Standard bow rope Standard foot strap | | Air Hull IRB Alternative bow rope Standard foot strap | | Mean loading |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LTB | RTB | LTB | RTB | LTB | RTB | LTB | RTB | LTB | RTB | LTB | RTB | |
| P1 | 39 | 68 | 42 | 76 | 29 | 29 | 35 | 67 | 17 | 29 | 13 | 20 | 39 |
| P2 | 34 | 35 | 31 | 38 | 23 | 26 | 13 | 27 | 47 | 23 | 15 | 18 | 28 |
| P3 | 46 | 54 | 14 | 29 | 20 | 41 | 18 | 30 | 12 | 20 | 13 | 18 | 26 |
| P4 | 20 | 23 | 14 | 15 | 28 | 28 | 19 | 17 | 17 | 13 | 16 | 12 | 18 |
| Mean Crew (P1&3) | 43 | 28 | 28 | 53 | 24 | 35 | 26 | 48 | 14 | 24 | 13 | 19 | 30 |
| Mean Drivers (P2&4) | 27 | 29 | 23 | 27 | 26 | 27 | 16 | 22 | 32 | 18 | 15 | 15 | 23 |

*All units: g; Trials are highlighted in accordance with greatest loading of >40g*
*LTB Left tibia, RTB right tibia*

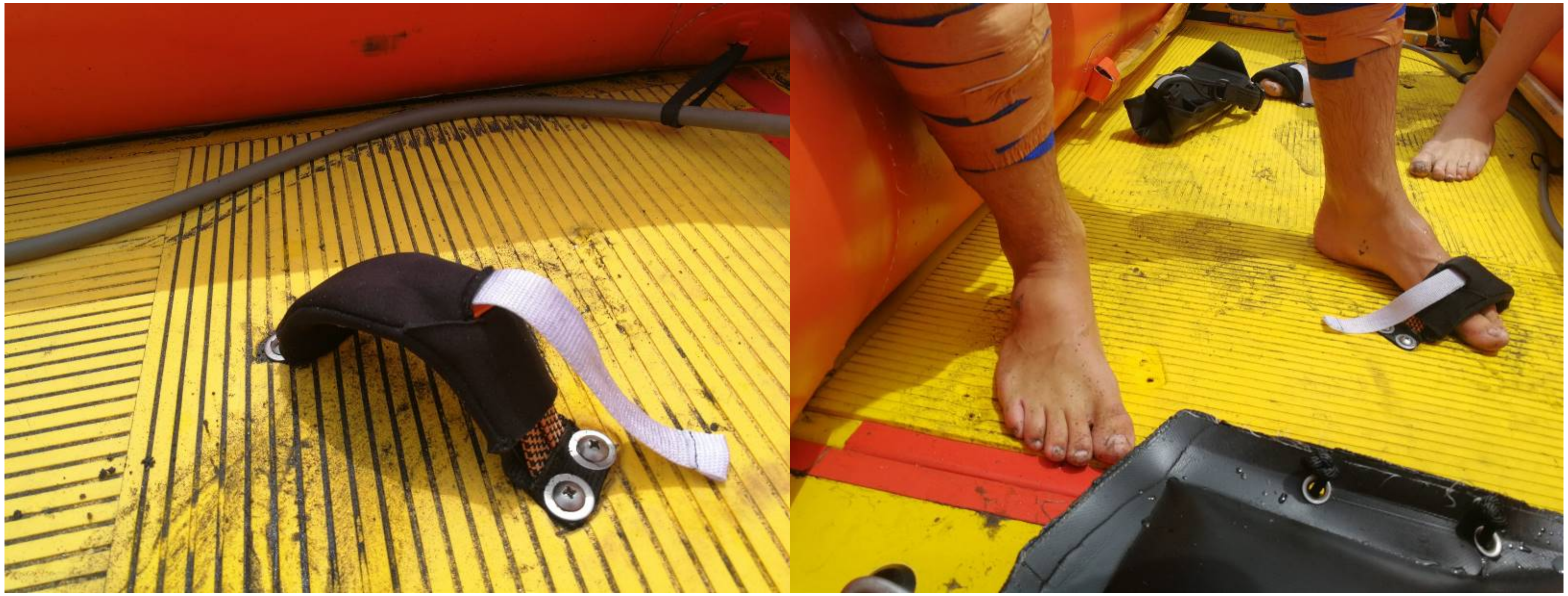


**Figure 18. The foot strap during fitting with the crew.**

During and following the on-water sea trials, the AUT foot strap limitations were considered. Once issue which arose was that the AUT foot strap had too much give, resulting in one crew member's foot nearly slipping straight through the strap. Redesign to reduce the amount of bungee material used will allow for increased stability. Further consideration should be given to whether the bungee feature could be used for the right foot only. The ability to adjust the foot strap with ease was considered a positive attribute. However, as the cambuckle did become exposed at various points during the sea trials and at times, hit the crew person's ankle, more padding was needed for future designs.

**Features of the foot strap that were redesigned based on the feedback gained during the sea trial included reduced bungee, alteration of the pull strap to heavy-duty polywebbing and increased sleeve coverage (Figure 19).**


**Figure 19. AUT foot strap features which were redesigned in accordance with feedback gained during the sea trials.**

***Comparison of existing and AUT foot strap designs***

The foot straps currently used in IRBs pose potential risks due to the 'one size fit all' approach. This approach puts surf lifesaving personnel at risk as smaller feet may slide and cause entrapment-centered injuries and larger feet may become 'jarred' in the foot strap. Consequently, the increased circumference of the AUT strap was designed to well exceed the needs of most, if not all, users. The standard foot strap additionally uses rigid material with minimal give, thereby increasing the potential for ankle injury. Feedback during the sea trials indicated that while the AUT designed prototype foot strap design did not reduce loadings on tibia, they significantly increased crew foot comfort and account for ranging foot sizes which was overlooked in the previous foot strap design. To limit the risk of potential harm to the feet and ankles in urgent situations, the quick adjustable feature that the AUT foot strap encompasses is an additional positive feature. The quick release feature in addition to use of a bungee appears to alleviate the risk of potential entrapment as, if ever necessary, the crewperson can release themselves from the foot strap.

## DISCUSSION

**BODY LOADS DURING SURF LIFESAVING IN IRB'S**

To provide insight into the high prevalence of lower limb injuries sustained in the surf lifesaving population, the current study aimed to investigate lower limb loading during IRB impacts in-lab and on-water, in addition to kinematic analysis of lower limb angles at the point of impact. Lower limb loading was substantial, particularly during sea trials. The maneuvers performed were typical of that within a training exercise or rescue and are therefore highlight an issue of concern in the way of potential injury risk exposure to the cohort.

***Varying speed across conditions***

The speed at which the IRB crew engage with a wave, i.e. driver behaviour, along with the IRB rigidity/flexibility, are routinely described by crews as contributing factors to crew comfort and safety. Both the IRB crews reported operating the prototype air hull at lower speeds than the standard IRB hull. The crews identified their lack of familiarity with the prototype air hull and its instability during operation as the primary cause to limit the speed of the prototype air hull during the sea tests for crew safety, which are likely to have contributed to the lower forces identified in this investigation.

***Magnitude of load and risk of injury***

The high magnitude impacts in combination with the high frequency (repetitions) of impacts in the data set presented provides insight into the mechanism of injury which likely contributes to the lower limb injuries sustained while using IRBs in some surf lifesaving operational contexts.

**BOAT DESIGN EFFECTS ON TIBIAL LOADING**

The study investigated several modifications to standard IRBs, including foot straps, bow ropes and hull characteristics to try to limit the load and likelihood of harm to users, particularly crewpersons. The most favorable IRB set-up which incurred lower limb loading of 13g in the crew and 15g in the drivers, was the prototype air hull IRB with the alternative rope and standard foot strap, although the limits of the foot strap design may not have benefited these reduced loads. This condition reduced tibial loading between 3.2 and 1.9 times that experienced in the standard conditions currently used in surf lifesaving practice (standard IRB, standard bow rope, standard foot strap). This finding therefore provides support for the ability of modifications to reduce lower limb loading during IRB impacts. Informed by the loading findings during sea trials, future research should consider combining the AUT foot strap and prototype air hull IRB to further investigate methods in which lower limb loading may be reduced during surf lifesaving.

***Foot straps***

The results indicate a positive trend when using the AUT foot strap, in comparison with the standard foot strap. As the AUT foot strap was a prototype, it is likely that future versions of the foot strap, which are tailored through insight from SLSNZ and the AUT design team, may contribute to a further reduction in lower limb loading.

***Right versus left tibia loading***

The results highlight increased loading of the right tibia compared to the left during both the in-lab and on-water collections. The distribution of loading may be alleviated to some extent if cushioning material is incorporated into IRB design, although this is speculative and beyond the scope of the current study. Therefore, this area would benefit from further research.

In-lab data provided quantification of loading and body positioning at peak impact when only the left foot was in a foot strap, compared to when both feet were in foot straps. This modification is already seen across surf lifesaving in NZ, yet this is the first study to the researchers' knowledge, which has evidenced the mechanical influence on the body. The findings showed using the left foot strap alone generally reduced left tibia loading. Kinematic data showed that with the left foot strap only, the left limb underwent a reduction in knee adduction, increase in knee flexion and increase in ankle dorsiflexion. The findings show a positive kinematic trend towards a technique which may be favorable for reducing impact loading and may contribute to reduced injury risk. However, the findings were not conclusive across all conditions and participants. Therefore, the laboratory kinematic findings should be interpreted with some caution for generalization to all surf lifesavers until a larger sample of surf lifesavers are tested.

***Bow ropes***

Although the alternative bow rope had some potentially positive effects on crewperson's stability, it did not appear to influence right tibia loading. Further analysis which incorporates stability analyses may be beneficial to better appraise the influence of bow rope design on injury potential. Therefore, further collaboration to explore options to reduce tibial loading would be beneficial.

***Boat hull***

The material properties which the IRB crew are landing on will influence the level of loading experienced at impact. The results from the current study provide indication of a positive trend, by way of reduced loading, with the prototype air hull IRB. Although this is logical (i.e. softer landing and a greater absorption of energy by the IRB, rather than the lower limbs), this finding should be interpreted with some caution as the participants had not had prior exposure to the prototype air hull IRB. Therefore, it is likely that lack of comfort with the boat would lead to increased caution by way of slower IRB velocity. Although the findings from this study suggest the potential for alteration of the boat hull to reduce injury potential, further research is necessary to eliminate the confounding variables encompassed within this study, e.g. the small sample size.

***Crew versus driver***

The findings from the on-water collection emphasized the increased loading experienced by crew members in comparison to drivers. With the positioning of the crew in the IRB and proximity to the oncoming waves, the research findings give clear indication for the need to focus on the reduction of loading experienced by crew members. The current research offers insight into some ways in which this issue may be approached from a mechanical standpoint, however, the heightened risk of the crew member should additionally be approached from a personal development/behaviour standpoint. Increased awareness of the heightened loads experienced by crew members should be emphasised within the SLSNZ community. As the driver is in control of the IRB placement and speed, the drivers' responsibilities to act in a manner to best reduce the loading experienced by the crew is crucial. Further studies on driver behavior and the interplay between driver and crew is warranted to develop a holistic appreciation for the reduction of on-water injuries in surf lifesaving.

***IRB experience level***

From the interviews conducted during the in-lab testing, the participants indicated the importance of experience level in relation to injury potential. Although experience-related conclusions cannot be drawn from the current loading outputs, this is a factor which should be considered within future research.

***In-lab versus on-water***

Although the in-lab testing provided an indication of lower limb positioning at impact, the loads experienced on water were typically more than double those experienced in-lab. Therefore, kinematic data should be used as a guide to consider lower limb positioning independent of loading experienced. The maximum average load experienced on-water across participants was 53g, with the right tibia undergoing loading of 76g for one participant.

Given the in-lab testing showed that loading could be reduced with changes in lower limb biomechanics via knee and ankle angle changes during landings, further work should examine what techniques would lower impact loading during on-water landings.

**LIMITATIONS TO THE STUDY AND THEREFORE IMPLICATIONS FOR INTERPRETATION OF THE FINDINGS**

***On-water wave conditions***

On-water wave conditions were not the same for each trial within a condition, nor for trials for the more experienced males versus the females' boat conditions. The waves were larger in the morning for the female's trials.

***Surf lifesaving experience***

The males were more experience than their female counterparts.

***IRB familiarity***

All participants had an opportunity to become familiar with the different bow rope setups during the in-lab testing, however, the on-water testing was the first time the different conditions had been used in practice. In addition, the participants had no prior exposure to the new foot strap and the prototype air hull IRB.

***Alternative bow rope length***

Participants were able to determine the optimal length of the bow rope, thereby individualizing the condition. The rope length determined when on shore immediately before testing on-water and therefore, had the participants had a few days/weeks to get used to the alternative rope, the selected length may have differed from that included within the on-water testing.

**POTENTIAL CONSIDERATIONS FOR SLSNZ AS A RESULT OF THE FINDINGS FROM THE STUDIES**

- Ongoing development of the AUT foot strap modifications following a period of prolonged familiarization.
- Understanding of any further limitation of the AUT foot straps experienced during rescue practice
- Consideration of material used under feet – hull or cushioning under foot placement area
- Further testing and potential re-design of the bow rope

**CONSIDERATIONS FOR FUTURE RESEARCH**

Although sacral acceleration data were not appraised in the current study into lower limb injury potential, analysis of mechanisms for lower back injury potential may be warranted in future research due to the seriousness of such injuries in conjunction with the high incidence rates in surf lifesavers (SLSNZ technical report #2). As the mechanisms for lower back injury potential differ to those at the ankle/lower limbs, distinct analyses would be required to extract meaningful data outputs in relation to lower back injury risk. A separate study into the unique mechanisms of injury in this region may be an important contribution to future surf lifesaving literature, and potential reduction in future lower back injuries.

Initial insight into the importance of driver behavior on injury potential was highlighted through interviews with current surf lifesaving members. Additional investigation into on water driver behavior should be undertaken to further understand the role of behavior in injury risk.

## CONCLUSIONS

The magnitude of lower limb loading experienced during the surf lifesaving study was substantial compared with other activities such as basketball jumping. Therefore, every effort should be made to reduce the magnitude and frequency of IRB impacts to prevent acute and overuse lower limb injuries.

A key finding from the research was that modifications to IRB features can positively influence acute loading experienced by surf lifesaving personnel. The study findings indicated a positive trend for the reduction of lower limb loading when using the AUT foot strap compared with the standard foot strap. The prototype air hull IRB showed a positive trend of reducing lower limb loading when compared with the standard hull. As it is likely the cushioning effect of the prototype air hull, along with the reduced speed of the prototype air hull contributed to the reduction of lower limb loading. This suggests these finding provide support for the consideration of cushioning devices within IRB designs, as well as influencing driver behaviour, i.e. reduce speed where practicable.

Although loading differences were evidenced between bow rope variations, no clear conclusions of the relationship between bow rope design and lower-limb loading were established. The purpose of the modified bow rope configurations was primarily to increase crew persons' stability within the IRB, with the reduction of loading considered a secondary purpose. As indicated by participants, the multi-point attachment configurations were found to provide a degree of stability over and above the standard bow rope, however, further measures are required to objectively quantify if stability is altered with bow rope modifications.

The current research has provided evidence that IRB modifications may offer positive mechanical alterations to the body to contribute to the reduction of lower-limb injury risk in surf lifesaving. To advance the current study findings, future research should seek to fine-tune and continue the development of IRB configurations. To complement the mechanical insight gained, greater understanding of the physical consequences of driver behavior and crew-driver interplay is additionally warranted.

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