**Title**

Validating accelerometers to predict stroke rate using captive fur seals and sea lions

**Running title**

Predicting stroke rates from accelerometers

**Authors**

Monique A. Ladds1,2\*, David A. Rosen3, David J. Slip2,4, and Robert G. Harcourt2

1School of Mathematics and Statistics, Victoria University of Wellington, Wellington, New Zealand 6140

2Marine Predator Research Group, Department of Biological Sciences, Macquarie University, North Ryde, NSW Australia 2113

3Marine Mammal Research Unit, Department of Zoology, University of British Columbia, Vancouver, BA Canada

4Taronga Conservation Society Australia, Bradley's Head Road, Mosman, NSW Australia 2088

\*Author for correspondence ([monique.ladds@vuw.ac.nz](mailto:monique.ladds@vuw.ac.nz); ph: +644-463-5663; fax: +644-463-5045)

**Summary statement**

Accelerometer data collected from captive fur seals and sea lions swimming was used to validate the optimal method for processing raw data to achieve the highest accuracy of stoke rate.

**Key words**

Otariid, swim mechanics, energetics, stroke rate, accelerometer

**Abstract**

Energy expenditure of free-living marine mammals is a vital currency to measure, but it is difficult to do so directly. An affordable, non-invasive, easy to interpret proxy for energy expenditure, such as measuring stroke rate, is a potential solution for this difficult task. Stroke rate is the driver of most mechanical output of fur seals and sea lions (otariids) while at sea and can potentially be measured from small and cost-effective accelerometers. However, estimating the actual number of strokes from an accelerometer depends on the processing of the raw data, and is yet to be validated for otariids. We videoed 10 captive otariids swimming underwater in two conditions; either wearing a harness with the accelerometer recording at 32Hz (N = 4) or with the accelerometer recording at 25Hz taped onto the fur (N = 6). We used 25 combinations of two parameters (running mean and gradient) to test the estimated stroke rate from the accelerometers by comparing these with the actual number of strokes counted from videos. We used a range of running means (0.4, 1, 2, 3 and 4 seconds) to smooth the acceleration data and five different gradients (the minimum number of consecutive positive data points) to detect a peak in acceleration that corresponded to a stroke. We tested all 25 combinations using the data from the x-axis, the z-axis and the x+z axes to determine if we could determine stroke rate from a single axis. We found that the running mean selected had little effect on the overall predictions, while using the x-axis only generally resulted in fewer errors. The performance of gradients was related to the rate of recording, where a higher gradient worked best for higher rates of recording. Over the range of parameters tested, total number of strokes were over-or under-estimated by up to ~20%. We simulated the effect of different gradients (using a running mean of 3 seconds) to estimate stroke rate on the energy expended from a typical foraging trip of a female fur seal, and found that selecting a sub-optimal gradient (from the range of values tested here) would result in overall under- or over-estimation of energy expenditure of 7000-17500kJ over an entire foraging trip, which represented less than 1% of total energy typically expended. When parameters are appropriately tuned, accelerometers are a simple yet valid tool for estimating the stroke rates of swimming otariids.

**Introduction**

Measuring the energy expenditure of free living animals is an important but difficult task. For free swimming pinnipeds, numerous proxies for rates of energy consumption have been tried and tested with mixed results, including heart rate (Boyd et al., 1999), doubly labelled water (DLW) (Jeanniard-du-Dot et al., 2016a) and overall dynamic body acceleration (ODBA) (Fahlman et al., 2013). Among the inherent difficulties in using these measures is the fact that the predictive equations for each are liable to change with species, size of the animal, activity type, temperature, and digestive state (Fish, 2000; Ladds et al., 2016; Rosen et al., 2016). Therefore, it is unlikely there will ever be a universal method, or universal equation, that can accurately estimate energy expenditure for pinnipeds as a group. However, proxies can still provide important comparative information and may have important practical application. Measuring stroke rate is a relatively non-invasive method that has been suggested as having high potential for predicting energy expenditure in both otariid seals e.g. Northern fur seals (Jeanniard-du-Dot et al., 2016b) and in phocid seals e.g. Weddell seals (Williams et al., 2004). That stroke rate is a good predictor for these two species, which are evolutionarily divergent with completely different mechanics for underwater propulsion (otariids propel themselves using a sculling motion of their large fore-flippers (Feldkamp, 1987), while phocids rely on lateral movement of their hind flippers (Gallon et al., 2007)) suggests stroke rate might have wide application as a proxy for energy expenditure (Williams et al., 2004). Although stroke rate may seem a logical proxy for energy expenditure, there are questions regarding whether measures of stroke rate can be accurately obtained in free-swimming pinnipeds.

Pinnipeds perform long and deep dives traversing far-flung areas of the ocean while hunting and so are near impossible to observe *in situ* to count stroke rate. Animal borne cameras have been used to count strokes for some phocids seals, dolphins, and whales (Williams et al., 2000), but these devices are expensive, large and often fragile, with severe memory and battery limitations. While their use is insightful, simpler biotelemetry devices are much more widely deployed to provide insights on the location, physiology, and behaviour of seals at sea. Accelerometers are small, lightweight, and relatively cheap devices that measure the acceleration of the body on up to three axes, making them ideal for measuring stroke rate. Indeed, accelerometers have been successfully used to estimate stroke rates from a number of marine animals including penguins (Sato et al., 2011), seabirds (Lovvorn et al., 2004), fish (Broell et al., 2013) and sharks (Gleiss et al., 2009). They have also been used to estimate stroke rate for northern fur seals (*Callorhinus ursinus*) and Antartic fur seals (*Arctocephalus gazella*) (Jeanniard-du-Dot et al., 2016b), though the predictions were not validated.

Estimating stroke frequency from accelerometers assumes that the peaks in the outputs correspond to a stroke. Phocids stroke with their rear flippers with a lateral sway, therefore it is assumed that peaks in the sway axis (y axis) correspond to a stroke (Williams et al., 2004). Otariids use large fore-flippers to propel forward, therefore peaks in the surge (x axis), heave (z axis) or both axes are used to estimate strokes (Jeanniard-du-Dot et al., 2016b). Peak in lateral sway has been confirmed for Weddell seals using animal-borne cameras (Williams et al., 2004), but there is yet to be a validation study for otariids.

The task of delineating strokes from accelerometry data is highly dependent upon the processing of the raw data. For example, the choice of running mean influences the overall estimate (Shepard et al., 2008a). Estimating strokes from accelerometers requires appropriate smoothing of data and the choice of a minimum gradient to determine a peak in the data. The choice of these two parameters will influence the overall estimate and so should be tested across a range of values. Here, we evaluated the best parameters for calculating stroke rate for otariids swimming underwater using animals observed and filmed in aquariums while swimming and wearing accelerometers.

**Materials and Methods**

*Animals*

We conducted experiments between October and December 2014 at two research facilities: Underwater World (RF2: Mooloolaba, QLD, Australia) and Taronga Zoo (RF3: Sydney, NSW, Australia) with three New Zealand fur seals (*Arctocephalus forsteri*), two Australian fur seals (*Arctocephalus pusillus*) and four Australian sea lions (*Neophoca cinerea*)that were on permanent display at their respective marine facilities. We conducted experiments in November and December 2015 at the University of British Columbia’s Open Water Research Station (RF4: Port Moody, BC, Canada) with four Steller sea lions (*Eumetopias jubatus*) housed for research purposes (see Table 1 for details of the animals). All animals were non-reproductive during the study period and were cared for under the husbandry guidelines of the individual facility. All the Australian sea lions were born as a part of a captive breeding program ongoing in Australian aquaria, while all the fur seals came into captivity as juveniles having been found in poor health or injured and were considered unsuitable for release back into the wild after prolonged rehabilitation. All animals were in good health and condition as assessed by the in-house veterinary surgeon at the time of the experiments. All Steller sea lions were collected from breeding rookeries as pups and raised at the Vancouver Aquarium (British Columbia, Canada). Macquarie University ethics committee (ARA-2012\_064) and Taronga ethics committee (4c/10/13) approved experiments conducted in Australia. All animal handling and experimental procedures in Canada were conducted in accordance with regulations of the Canadian Council on Animal Care (University of British Columbia animal use permit #A11-0397), Department of Fisheries and Oceans Canada (MML 2007-001) and the Vancouver Aquarium.

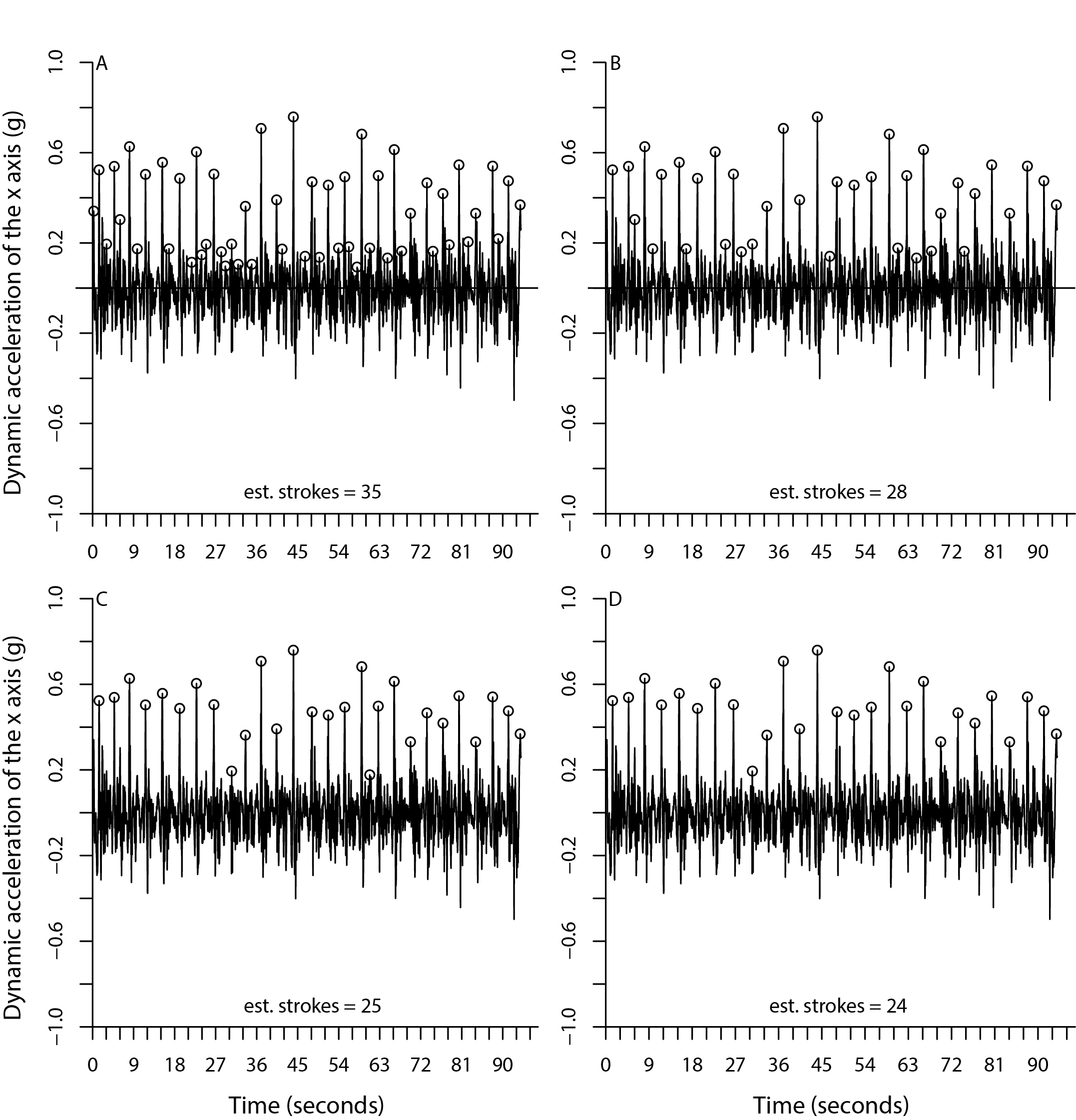
*Trial protocol*

During all experiments otariids were equipped with a 3-axis accelerometer (RF1-3: CEFAS G6a+, ±8g, 40 × 28 × 16.3 mm and mass 18 g in air and 4.3 g in seawater, CEFAS technology Ltd, Lowestoft, UK; or a RF4: Daily Diary, 95 × 45 × 26 mm, 90 g, Wildlife Computers; Table 1.) They were also recorded with an array of static underwater cameras (GoPro Hero 3 Black edition, 1080p / Wide / 60fps). All sea lions (except ASM2) wore a tight-fitting harness which held the accelerometer on the centre of the dorsal surface while for all fur seals (and ASM2) the accelerometer was attached between the shoulder blades with Tesa tape. Sea lions at RF4 had been trained to swim underwater between two submerged feeding stations (Rosen et al., 2016) while otariids at RF1-3 were trained to swim laps of a pool between two stationary targets. All animals were familiar with the experimental equipment and performed all trials voluntarily under trainer control.

*Stroke rate estimation*

Accelerometers (described above) recorded time, depth, and acceleration on 3 axes: anterior-posterior (surge), lateral (sway) and dorso-ventral (heave), from which the stroke rate, were extracted (see below). Video footage from RF2, RF3 and RF4 was pseudo-randomly collected with 10 animals participating in other experiments (Ladds et al., 2016) from which we could directly count stroke rate. Underwater swimming at RF2 and RF3 was recorded with GoPro HERO3 (GoPro, USA) mounted inside PVC pipes each with a viewing window cut-out that were placed in the pool during trials (see Hocking et al., 2015 for a figure of the set up). Sea lions at RF4 had the GoPro mounted to their harness and oriented towards the pectoral flipper. Videos were downloaded and edited together in Adobe Premiere Pro (Adobe Systems Incorporated, California), before being exported at the same frame rate as the accelerometer recorded (i.e., G6a+ 25 FPS and 25Hz at RF1-3; Daily Diary 32 FPS and 32 Hz at RF4). Accelerometer data were matched with the corresponding frame rate on the video, allowing us to extract data for dives.

The dynamic acceleration was then used to predict stroke rate, where strokes were identified as peaks in the x-axis (see Fig. 1, and description below). Actual total stroke number for a trial was counted from videos of individual trials, where a stroke was counted if a complete cycle of movement of the flipper was completed. Strokes that used a single flipper or that were only below the body were not included as they were often masked on the accelerometry by other movement. The accelerometry data is first smoothed using a running mean to remove the effect of gravity from the data. To detect a stroke a suitable gradient must be selected to detect a peak in the smoothed accelerometry. A peak is detected by calculating the signed difference iteratively of the smoothed data, then assigns a peak if the data are positive for the minimum amount of time set by the gradient. For example, if the minimum gradient is 10, then if there are at least 10 consecutive positive differences a peak will be marked at the end of the run of positive numbers (before the next negative number). The running mean used and the gradient of the peak affected the overall ability of the peaks to predict total stroke rate, therefore a combination of these variables was created and tested for their ability to predict total strokes for a dive.



**Figure 1. Dynamic acceleration of the x axis from a running mean of 1 second with different gradients applied to find peaks.** A – gradient = 10; B - gradient = 20; C - gradient = 30; D - gradient = 40. Actual number of strokes for this sample (as determined by video footage) was 26.

*Statistical analysis*

As the recording rate and the attachment method of the accelerometers differed for some of the animals the analysis was carried out for two groups – the tape group (recording at 25Hz and accelerometer was taped to the fur) and the harness group (recording at 32Hz and the accelerometer was fitted to a harness). Stroke rate was estimated from peaks in the dynamic acceleration of the x, z and x + z axes. Peaks were extracted from the accelerometry data based on a minimum gradient before a peak. Since both the running mean and the minimum gradient of the peaks influenced the overall stroke rate estimate, combinations of these two variables were created. The running means tested were 0.4, 1, 2, 3 and 4 seconds and the gradients tested were 10, 20, 30, 40 and 50 (Fig. 1) for the tape group and 60, 70, 80, 90 and 100 for the harness group. The gradients differed for the two groups as the accelerometers were recording at different Hz; higher Hz resulted in more data being recorded which required a higher gradient. The best stroke rate prediction was defined as the running mean and gradient that resulted in the fewest errors when compared to observed stroke rates (Fig. 3). This was determined by testing if the differences were significantly different from 0, meaning no difference in observed and measured strokes, using a one-sample Z-test.

To assess the impact of the different stroke estimates we investigated how they would affect overall energy expenditure estimation. The expected energy expended from each dive was calculated for both groups by multiplying the total number of actual strokes and estimated stroke rates for that dive by 7.9 J/kg/stroke. We chose this value as it was the estimated cost of a stroke similarly sized Southern sea lions (*Otaria ﬂavescens*) (Dassis et al., 2012). As this was an exercise in the utility of using stroke rate as a measure of energy expenditure we did not test all combinations of running mean and gradients. Instead for the estimated stroke rates we used a running mean of three seconds (as this is a commonly used smoother in the literature) and a range of gradients: 20,30, 40 and 50 for the tape group and 60, 70, 80 and 90 for the harness group. For each dive, the estimated energy expended for the actual number of strokes was subtracted from the estimated energy expended for the estimated stroke rate. The difference in energy expenditure was then plotted on histograms for comparison.

All analysis was completed in R (Version 3.1.3; R Core Development Team, 2015) and values are reported as mean ± SD.

**Table 1. Seal characteristics and summary metabolic rates from all trials.** Species, ID, mass (kg), age (years) and marine facility where housed, type of accelerometer used, recording rate and method of attachment for five fur seals and eight sea lions. Marine facility: RF2 – Underwater World; RF3 – Taronga Zoo; RF4 – Open Water Research Station.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Species | ID | Mass | Age | Marine | Device | Recording | Attachment |
|  |  |  |  | **facility** |  | **rate** | **method** |
| Australian fur seal | AFF1 | 69-78 | 17 | RF2 | G6a+ | 25Hz | Tape |
| AFM1 | 179-182 | 14 | RF2 | G6a+ | 25Hz | Tape |
| Australian sea lion | ASM1 | 153-160 | 12 | RF3 | G6a+ | 25Hz | Tape |
| New Zealand fur seal | NFM1 | 54-55 | 8 | RF3 | G6a+ | 25Hz | Tape |
| NFM2 | 149-161 | 11 | RF2 | G6a+ | 25Hz | Tape |
| NFM3 | 154 | 13 | RF3 | G6a+ | 25Hz | Tape |
| Steller sea lion | F00BO | 155-160 | 15 | RF4 | Daily Diary | 32Hz | Harness |
| F97HA | 172-175 | 18 | RF4 | Daily Diary | 32Hz | Harness |
| F97SI | 230-233 | 18 | RF4 | Daily Diary | 32Hz | Harness |
| F00YA | 214-218 | 15 | RF4 | Daily Diary | 32Hz | Harness |

**Results**

*Predicting stroke rates*

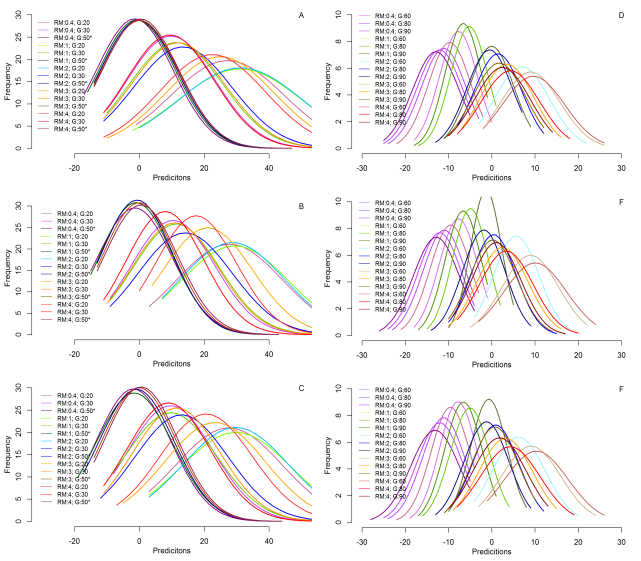
We tested 25 different combinations of minimum gradient before peak (n=5 levels; tape: 10-50; harness: 60-100) and running means (n=5 levels; 0.1-4 sec) to smooth data and evaluated the difference between predicted stroke rate and actual stroke rate. Stroke rate could be accurately predicted from finding peaks in the dynamic acceleration of all the axes tested (X, Z and X + Z axes), where no one axis was better at predicting stroke rate than another (Table 2). The accuracy of predictions depended predominantly on which gradient and running mean were used. The exact combinations of running mean and gradient required to achieve the lowest error rates for stroke prediction differed between individuals (Table 2). The absolute mean difference in the number of strokes predicted and the number of actual strokes for each dive across both groups was between 0 and 3.1, which represented a percentage difference of between -7.1 and 8.6% (Table 2). This demonstrates that stroke rate predictions were both over- and under-estimated depending on the animal and the running mean and gradient used.

**Table 2. Summary of the combination of running mean and gradient that best predicts stroke rate** **for five fur seals and five sea lions**. With the mean of the difference and the percentage difference between the predicted and actual number of strokes for that combination and number of trials.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ID | Method | N | Best running | | | Best | | | | Mean | | | | Difference | | | | |
|  |  |  | **mean (secs)** | | | **gradient** | | | | **difference** | | | | **%** | | | | |
|  |  |  | X | Z | XZ | | X | Z | XZ | | X | Z | XZ | X | Z | XZ | |
| Australian fur seal | | | | | | | | | | | | | | | | |
| AFF1 | Tape | 12 | 4 | 0.4 | 0.4 | | 40 | 40 | 40 | | 0.2 | 0.1 | 0.6 | -3.7 | 0.5 | 1.9 | |
| AFM1 | Tape | 19 | 0.4 | 0.4 | 0.4 | | 50 | 50 | 50 | | 3.1 | 2.3 | 2.6 | -7.1 | -5.7 | -6.7 | |
| New Zealand fur seal | | | | | | | | | | | | | | | | |
| NFM1 | Tape | 12 | 0.4 | 4 | 4 | | 40 | 50 | 50 | | 0.5 | 0.2 | 0.1 | -2.1 | -1.3 | -1.5 | |
| NFM2 | Tape | 19 | 0.4 | 1 | 1 | | 50 | 50 | 50 | | 2.7 | 0.4 | 1.5 | -2.2 | -1.0 | -2.6 | |
| NFM3 | Tape | 7 | 1 | 1 | 0.4 | | 40 | 40 | 40 | | 0.0 | 0.4 | 0.0 | -0.3 | -5.8 | -2.6 | |
| Australian sea lion | | | | | | | | | | | | | | | | |
| ASM1 | Tape | 17 | 4 | 4 | 3 | | 30 | 40 | 40 | | 2.2 | 0.4 | 1.0 | -5.0 | -2.8 | -1.6 | |
| Steller sea lion | | | | | | | | | | | | | | | | | |
| F00BO | Harness | 14 | 3 | 4 | 2 | | 90 | 90 | 80 | | 0.1 | 0.1 | 0.2 | -1.0 | -0.8 | -1.6 | |
| F97HA | Harness | 7 | 2 | 4 | 4 | | 60 | 70 | 70 | | 1.0 | 0.9 | 0.1 | -3.2 | 8.6 | 2.5 | |
| F97SI | Harness | 9 | 2 | 2 | 2 | | 100 | 90 | 90 | | 0.6 | 0.6 | 0.6 | 2.7 | 1.0 | 8.3 | |
| F00YA | Harness | 19 | 2 | 1 | 1 | | 100 | 60 | 60 | | 0.2 | 0.1 | 0.5 | 4.4 | 2.0 | 5.0 | |

The output for the tape group revealed that the choice of axis and running mean were not important in predicting stroke rate correctly, but that a gradient of 40 or 50 was needed (Appendix B). Z-tests revealed that seven of the 25 running mean and gradient combinations were not significantly different from 0. When looking at the output for the harness group, there was no consistency in results for the choice of axis, running mean or gradient. Generally, a higher gradient (>70) and a higher running mean (>2 seconds) resulted in lower errors (Appendix C). Z-tests revealed that eight of the 25 running mean and gradient combinations were not significantly different from 0.

Figure 3 displays the distribution of errors for some selected combinations of gradients and running means. Distributions centred on 0 with small variances represent the best combinations, which differed for each attachment group. The best combination was chosen from the distribution that was not significantly different from 0 (observed = estimated) as determined by z-tests. For otariids with the harness, the best combination was a running mean of 1 second and a gradient of 60 using the x-axis only, as the errors are distributed around 0 with the least variance (Fig. 3C) and the differences were not significantly different to 0 (z = -0.1, p < 0.001; Appendix 1A). For otariids with the accelerometer taped on the best combination was a running mean of 3 seconds and a gradient of 50 using the x-axis only as the errors are distributed around 0 with the least variance (Fig. 3F) and the differences were not significantly different to 0 (z = 0.5, p < 0.001; Appendix 1B).



**Figure 3. Distributions of differences between predicted stroke rate and actual stroke rate over different running means and gradients.** A-C) otariids with the accelerometer taped on (N = 49 trials); D-F) otariids wearing a harness with the accelerometer (N = 71 trials). A and D – X axis; B and E – Z axis; C and F – X + Z axes.

*Energy expenditure from stroke rates*

Figures 4 and 5 demonstrate the expected over- or under-estimation in energy expenditure from calculating stroke frequency using different gradients and a running mean of three seconds. In Figures 4D and 5D the error is centred around 0, meaning that although on some dives the total number of strokes may be over- or under- estimated, over a long foraging trip these errors will be balanced across the overall energy estimation. However, if a different gradient was used, then the total number of strokes for a dive, and hence, the energy expenditure for that dive was generally underestimated, up to 225 J/kg for the harness group and up to 400 J/kg for the tape group. Most errors fell between ±100J/kg excess energy expenditure on each dive on a typical foraging trip of an otariid of 2500-4000 dives (Jeanniard-du-Dot et al., 2016b) could result in a ±250,000-400,000J/kg under- or over-estimation of energy expenditure for that trip.

Excess energy expenditure = ± 100J/kg × 3000 dives = ± 300,000 J/kg ~ ± 300 kJ/kg



**Figure 4. Potential energy loss or gain from over- or under- estimation of total stroke rate from different gradients for the tape group.** Data were estimated using data smoothed with a running mean of 3 seconds and multiplying the difference in number of strokes observed and estimated for a given dive by the cost of a stroke (7.9J/kg – see methods) for four different gradients: A – 20; B – 30; C – 40; D – 50.

****

**Figure 5. Potential energy loss or gain from over- or under- estimation of total stroke rate from different gradients for the harness group.** Data were estimated using data smoothed with a running mean of 3 seconds and multiplying the difference in number of strokes observed and estimated for a given dive by the cost of a stroke (7.9J/kg – see methods) for four different gradients: A – 60; B – 70; C – 80; D – 90.

**Discussion**

This study demonstrates that the parameters chosen to tune the stroke rate calculation from accelerometers can affect the overall estimate. Here we tested different combinations of running means to smooth the data and gradients that determine a peak in the smoothed acceleration that corresponds to a stoke. Accelerometry data consists only of peaks and troughs (Fig. 1), therefore it is important to choose a gradient that corresponds only to a stroke and not to other movement of the body. Choosing the correct combination of running mean and gradient to predict stroke rate is important because total number of strokes could be under- or over- predicted by ~20%. However, if the goal of the research is to predict energy expenditure from strokes then this error will have little effect on the overall estimate. On a typical foraging trip of an otariid performing between 2500-4000 dives the over- or under-estimated energy expenditure would typically be between 200-500kJ/kg. For a 35kg animal this is a gain or loss of 7000-17500kJ over an entire foraging trip. If on a typical foraging trip 140MJ are expended (Jeanniard-du-Dot et al., 2016b) the expected gain or loss in energy expenditure is less than 1%. Therefore, while accuracy may be lost from estimating the total number of strokes on a foraging trip, if the goal is to use stroke rate to estimate energy expenditure a relatively wide range of parameters are available to use which will result in low errors.

These results show that for accurate prediction of stroke rate for otariids the gradient used to detect a peak in the accelerometery is the most important parameter. Accelerometers measure the movement of an animal in three directions – surge, heave and sway – and the amplitude of these measurements are dependent on the activity of the animal. The stroke pattern of otariids causes a surge of acceleration forward (x-axis) and upward (z-axis), which results in steep peaks in these two axes (Jeanniard-du-Dot et al., 2016b). Here we have shown that these steep peaks can be identified using a minimum gradient (Fig. 1), which were confirmed to match the strokes of the individual with video analysis. For otariids that have the accelerometer attached with tape a relatively shallow gradient can be used to detect strokes (40-50; Figure 1). For otariids with the accelerometer placed in a harness a steeper gradient was required to account for the noise in the data (90-100; Appendix C). A larger gradient was required for the otariids wearing harnesses because of the additional data generated from the higher sampling rate of the accelerometer (32 Hz vs 25 Hz) and movement from the harness. The running mean chosen did not have a large influence on the overall prediction of stroke rate. Dynamic body acceleration (DBA) is derived from applying a running mean over the axes of acceleration to calculate static acceleration (gravity) and removing this from the raw acceleration (Shepard et al., 2008b). The value used to calculate the running mean changes the value of the DBA, and thus affects the ability of DBA to predict energy expenditure and to calculate an accurate estimate of stroke rate (Shepard et al., 2008a).

Accelerometer attachment (tape or harness), running mean and the axis (or combination of axes) used each had some effect on the results, but overall were not important in accurately predicting stroke rate. For animals wearing a harness, as the accelerometer was recording at a higher rate, a steeper gradient was required as more peaks and troughs were evident in this data. However, sharp jolts by the animal (such as stopping suddenly) did cause a spike in the accelerometry data that was interpreted as a stroke. This did not appear to occur with the animals that had the accelerometer attached with tape. Investigations of wild pinnipeds generally involve the device being glued to the animal, which is analogous to the tape method, suggesting wild studies will not be adversely affected. However, future studies investigating stroke rate in captivity can still use harnesses to attach devices, provided the noise in the data is accounted for by changing the gradient. This is important for animals such as sea lions where attachment of devices with tape in captivity is difficult because the hair is too short (M. Ladds pers. comm.) or when multiple devices must be placed on the animal to measure activity in the open water (Rosen et al., 2016).

While the miniaturisation of data-loggers is making it easier to collect data from free-living animals, data storage can still be an issue, particularly if the goal is to monitor the animal over a long period. We found little variation between the ability of a single axis compared to a combination of axis to predict stroke rate. This suggest that if memory or power of a logger that is to be deployed for long durations is limited, it is still possible to obtain good stroke rate measures using only a single axis – x (Halsey et al., 2009) i.e. measuring only this axis allows for robust prediction of stroke rate in otariids. Sample rates of the accelerometers may also affect the ability to predict stroke rate from accelerometers, with lower rates of sampling being more variable, and predictions more robust at rates greater than 0.2Hz (Halsey et al., 2009). As we were measuring well above this frequency (25 and 32Hz) sampling frequency was not a confounding factor when estimating stroke rate in our study. Potentially this means that in wild studies a much lower sampling frequency could be used, saving battery and memory of devices, allowing them to be deployed for much longer durations (Halsey et al., 2009).

*Conclusion*

Stroke rate may be a useful proxy for estimating energy expenditure (Jeanniard-du-Dot et al., 2016b), but as with any proxy, it is important that steps are taken to validate its utility. Here we attached accelerometers, recording at different rates, to fur seals and sea lions swimming under controlled conditions. We found that recording rate of the accelerometer required that a steeper gradient was used to account for the additional data (and thus peaks) recorded from the accelerometer. Further, the running mean selected had little influence on the accuracy of the estimated number of strokes. Changing the gradient used to identify strokes can impact on the overall estimation of energy expenditure, but over an entire foraging trip the error would be less than 1%. Therefore, when using accelerometers to estimate stroke rate for otariids any running mean of between 1 and 4 seconds is appropriate, measured on a single axis (x or z). However, the gradient used must be selected according to the sampling rate of the accelerometer, where a higher gradient is required for a higher sampling rate. This study shows that accelerometers are a simple yet valid tool for estimating the stroke rates of swimming otariids provided that care is taken in selecting the appropriate gradient for identifying peaks in the accelerometry.

**References**

**Boyd, I., Bevan, R., Woakes, A. and Butler, P.** (1999). Heart rate and behavior of fur seals: Implications for measurement of field energetics. *American Journal of Physiology-Heart and Circulatory Physiology* **276**, H844-H857

**Broell, F., Noda, T., Wright, S., Domenici, P., Steffensen, J. F., Auclair, J.-P. and Taggart, C. T.** (2013). Accelerometer tags: detecting and identifying activities in fish and the effect of sampling frequency. *J. Exp. Biol.* **216**, 1255-1264

**Dassis, M., Rodríguez, D. H., Ieno, E. N. and Davis, R. W.** (2012). Submerged swimming and resting metabolic rates in Southern sea lions. *J. Exp. Mar. Biol. Ecol.* **432-433**, 106-112. 10.1016/j.jembe.2012.07.001

**Fahlman, A., Svärd, C., Rosen, D., Wilson, R. and Trites, A.** (2013). Activity as a proxy to estimate metabolic rate and to partition the metabolic cost of diving vs. breathing in pre-and post-fasted Steller sea lions. *Aquatic Biol.* **18**, 175-184. 10.3354/ab00500

**Feldkamp, S.** (1987). Swimming in the California sea lion: morphometrics, drag and energetics. *J. Exp. Biol.* **131**, 117-135

**Fish, F. E.** (2000). Biomechanics and energetics in aquatic and semiaquatic mammals: Platypus to Whale. *Physiol. Biochem. Zool.* **73**, 683-698. 10.1086/318108

**Gallon, S. L., Sparling, C. E., Georges, J. Y., Fedak, M. A., Biuw, M. and Thompson, D.** (2007). How fast does a seal swim? Variations in swimming behaviour under differing foraging conditions. *J. Exp. Biol.* **210**, 3285-3294

**Gleiss, A. C., Gruber, S. H. and Wilson, R. P.** (2009). Multi-Channel Data-Logging: Towards Determination of Behaviour and Metabolic Rate in Free-Swimming Sharks. In *Tagging and Tracking of Marine Animals with Electronic Devices*, eds. J. L. Nielsen H. Arrizabalaga N. Fragoso A. Hobday M. Lutcavage and J. Sibert), pp. 211-228. Dordrecht: Springer Netherlands.

**Halsey, L. G., Green, J. A., Wilson, R. P. and Frappell, P. B.** (2009). Accelerometry to estimate energy expenditure during activity: best practice with data loggers. *Physiol. Biochem. Zool.* **82**, 396-404. 10.1086/589815

**Hocking, D. P., Fitzgerald, E. M., Salverson, M. and Evans, A. R.** (2015). Prey capture and processing behaviors vary with prey size and shape in Australian and subantarctic fur seals. *Mar. Mamm. Sci.* **32**, 568-587. 10.1111/mms.12285

**Jeanniard-du-Dot, T., Guinet, C., Arnould, J. P. Y. and Trites, A. W.** (2016a). Accelerometers can measure total and activity-specific energy expenditure in free-ranging marine mammals only if linked to time-activity budgets. *Funct. Ecol.* 10.1111/1365-2435.12729

**Jeanniard-du-Dot, T., Trites, A. W., Arnould, J. P., Speakman, J. R. and Guinet, C.** (2016b). Flipper strokes can predict energy expenditure and locomotion costs in free-ranging northern and Antarctic fur seals. *Sci. Rep.* **6**, 33912. 10.1038/srep33912

**Ladds, M., Slip, D. and Harcourt, R.** (2016). Swimming metabolic rates vary by sex and development stage, but not by species, in three species of Australian otariid seals. *J. Comp. Physiol. B*. 10.1007/s00360-016-1046-5

**Lovvorn, J. R., Watanuki, Y., Kato, A., Naito, Y. and Liggins, G. A.** (2004). Stroke patterns and regulation of swim speed and energy cost in free-ranging Brünnich's guillemots. *J. Exp. Biol.* **207**, 4679-4695

**R Core Development Team.** (2015). R: A language and environment for statistical computing. In *R version 3.3.1*. Vienna, Austria: R Foundation for Statistical Computing.

**Rosen, D. A. S., Hindle, A. G., Gerlinsky, C. D., Goundie, E., Hastie, G. D., Volpov, B. L. and Trites, A. W.** (2016). Physiological constraints and energetic costs of diving behaviour in marine mammals: a review of studies using trained Steller sea lions diving in the open ocean. *J. Comp. Physiol. B*, 1-22. 10.1007/s00360-016-1035-8

**Sato, K., Shiomi, K., Marshall, G., Kooyman, G. L. and Ponganis, P. J.** (2011). Stroke rates and diving air volumes of emperor penguins: implications for dive performance. *J. Exp. Biol.* **214**, 2854-2863. 10.1242/jeb.055723

**Shepard, E. L., Wilson, R. P., Halsey, L. G., Quintana, F., Laich, A. G., Gleiss, A. C., Liebsch, N., Myers, A. E. and Norman, B.** (2008a). Derivation of body motion via appropriate smoothing of acceleration data. *Aquatic Biol.* **4**, 235-241. 10.3354/ab00104

**Shepard, E. L., Wilson, R. P., Quintana, F., Laich, A. G., Liebsch, N., Albareda, D. A., Halsey, L. G., Gleiss, A., Morgan, D. T. and Myers, A. E.** (2008b). Identification of animal movement patterns using tri-axial accelerometry. *Endang. Species. Res.* **10**, 47-60. 10.3354/esr00084

**Williams, T. M., Fuiman, L. A., Horning, M. and Davis, R. W.** (2004). The cost of foraging by a marine predator, the Weddell seal *Leptonychotes weddellii*: pricing by the stroke. *J. Exp. Biol.* **207**, 973-982. 10.1242/jeb.00822

**Williams, T. M., Davis, R., Fuiman, L., Francis, J., Le, B., Horning, M., Calambokidis, J. and Croll, D.** (2000). Sink or swim: strategies for cost-efficient diving by marine mammals. *Science* **288**, 133-136. 10.1126/science.288.5463.133

**Appendix A. Results for the tape group.**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Running mean** | **Gradient** | **Mean x** | **Mean z** | **Mean xz** | **Median x** | **Median z** | **Median xz** | **Range x** | **Range z** | **Range xz** | **SD x** | **SD z** | **SD xz** | **Z-test x** | **Z-test z** | **Z-test xz** | **Sig.** |
| 0.4 | 10 | 83.4 | 82.6 | 82.5 | 77 | 78 | 76 | 171 | 175 | 157 | 33.5 | 33.7 | 32.2 | 201 | 199 | 198.6 |  |
| 20 | 27.2 | 27.8 | 27.7 | 24 | 27 | 27 | 99 | 94 | 94 | 17.3 | 16.2 | 16.2 | 65.6 | 67 | 66.7 |  |
| 30 | 9.8 | 10.3 | 9.6 | 7 | 8 | 7 | 76 | 70 | 72 | 13.5 | 12.8 | 13.1 | 23.5 | 24.7 | 23.2 |  |
| 40 | 1.7 | 2.3 | 1.7 | -1 | -1 | -1 | 64 | 58 | 62 | 12.2 | 11.8 | 11.9 | 4.2 | 5.6 | 4.1 | \*\* |
| 50 | -1.5 | -1.5 | -1.9 | -3 | -4 | -4 | 60 | 56 | 57 | 11.7 | 11.6 | 11.5 | -3.6 | -3.6 | -4.6 | \*\* |
| 1 | 10 | 79.6 | 79.5 | 79.7 | 74 | 73 | 72 | 156 | 171 | 160 | 32.1 | 33.1 | 31.4 | 191.8 | 191.5 | 191.9 |  |
| 20 | 31.1 | 29.6 | 29.9 | 28 | 28 | 27 | 111 | 97 | 102 | 19.1 | 16.5 | 17.1 | 74.9 | 71.2 | 71.9 |  |
| 30 | 11.4 | 11.4 | 9.8 | 9 | 11 | 7 | 82 | 74 | 77 | 14.3 | 13.2 | 14 | 27.4 | 27.4 | 23.5 |  |
| 40 | 2.6 | 2.9 | 1.6 | 0 | 1 | -1 | 66 | 61 | 67 | 12.5 | 11.2 | 12.7 | 6.4 | 6.9 | 3.8 | \* |
| 50 | -0.8 | -1.1 | -1.6 | -3 | -3 | -3 | 58 | 55 | 60 | 11.8 | 11.1 | 11.8 | -1.9 | -2.7 | -4 | \*\* |
| 2 | 10 | 59.9 | 59.6 | 59.8 | 54 | 55 | 54 | 132 | 126 | 116 | 24.9 | 24.8 | 23.2 | 144.3 | 143.4 | 144 |  |
| 20 | 31.2 | 28.9 | 29.9 | 28 | 26 | 29 | 103 | 90 | 93 | 18.8 | 16 | 16.2 | 75.2 | 69.5 | 71.9 |  |
| 30 | 13.4 | 14.2 | 13.1 | 14 | 14 | 13 | 85 | 76 | 83 | 15 | 14.4 | 14.3 | 32.4 | 34.2 | 31.6 |  |
| 40 | 3.4 | 4.3 | 3.7 | 0 | 2 | 1 | 69 | 63 | 63 | 12.8 | 11.3 | 12.1 | 8.3 | 10.4 | 8.9 |  |
| 50 | -0.1 | -0.8 | -0.9 | -3 | -4 | -3 | 56 | 52 | 58 | 11.9 | 10.9 | 11.5 | -0.4 | -1.9 | -2.2 | \*\*\* |
| 3 | 10 | 56.7 | 54.5 | 56.3 | 52 | 50 | 52 | 128 | 105 | 106 | 23.7 | 20.6 | 22.1 | 136.7 | 131.2 | 135.5 |  |
| 20 | 24.9 | 21.2 | 23.4 | 24 | 19 | 23 | 102 | 74 | 89 | 16.5 | 13.8 | 15.4 | 59.9 | 51.2 | 56.4 |  |
| 30 | 12 | 11.1 | 11.5 | 10 | 9 | 10 | 87 | 74 | 77 | 14.4 | 13.1 | 13.4 | 28.9 | 26.7 | 27.8 |  |
| 40 | 4.1 | 5 | 4.8 | 0 | 3 | 2 | 68 | 64 | 63 | 12.7 | 11.4 | 11.6 | 10 | 12 | 11.5 |  |
| 50 | 0.2 | -0.1 | -0.1 | -2 | -3 | -3 | 59 | 53 | 56 | 11.9 | 11.1 | 11.4 | 0.5 | -0.3 | -0.2 | \*\*\* |
| 4 | 10 | 54.7 | 51.4 | 53.6 | 49 | 49 | 50 | 133 | 97 | 110 | 23.1 | 18.9 | 21.1 | 131.8 | 123.7 | 129.1 |  |
| 20 | 22.5 | 17.6 | 20.7 | 22 | 15 | 19 | 104 | 68 | 82 | 16.2 | 12.4 | 14.1 | 54.2 | 42.4 | 49.8 |  |
| 30 | 9.5 | 8.1 | 9.1 | 8 | 6 | 6 | 75 | 68 | 71 | 13.4 | 11.9 | 12.8 | 22.9 | 19.4 | 21.9 |  |
| 40 | 3.4 | 3.9 | 4 | 0 | 1 | 0 | 66 | 60 | 62 | 12.4 | 11.1 | 11.8 | 8.2 | 9.4 | 9.5 |  |
| 50 | 0.4 | 0.5 | 0.6 | -2 | -3 | -2 | 61 | 56 | 58 | 11.7 | 11.3 | 11.3 | 1 | 1.3 | 1.4 | \*\*\* |

**Appendix B. Results for the harness group.**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Running mean** | **Gradient** | **Mean x** | | **Mean z** | | **Mean xz** | | **Median x** | | **Median z** | | **Median xz** | | **Range x** | | **Range z** | | **Range xz** | | **SD x** | | **SD z** | | **SD xz** | | **Z-test x** | | **Z-test z** | | **Z-test xz** | | **Sig.** | |
| 0.4 | 10 | 83.4 | 82.6 | | 82.5 | | 77 | | 78 | | 76 | | 171 | | 175 | | 157 | | 33.5 | | 33.7 | | 32.2 | | 201.0 | | 199.0 | | 198.6 | |  | |
| 20 | 27.2 | 27.8 | | 27.7 | | 24 | | 27 | | 27 | | 99 | | 94 | | 94 | | 17.3 | | 16.2 | | 16.2 | | 65.6 | | 67.0 | | 66.7 | |  | |
| 30 | 9.8 | 10.3 | | 9.6 | | 7 | | 8 | | 7 | | 76 | | 70 | | 72 | | 13.5 | | 12.8 | | 13.1 | | 23.5 | | 24.7 | | 23.2 | |  | |
| 40 | 1.7 | 2.3 | | 1.7 | | -1 | | -1 | | -1 | | 64 | | 58 | | 62 | | 12.2 | | 11.8 | | 11.9 | | 4.2 | | 5.6 | | 4.1 | |  | |
| 50 | -1.5 | -1.5 | | -1.9 | | -3 | | -4 | | -4 | | 60 | | 56 | | 57 | | 11.7 | | 11.6 | | 11.5 | | -3.6 | | -3.6 | | -4.6 | | \* | |
| 1 | 10 | 79.6 | 79.5 | | 79.7 | | 74 | | 73 | | 72 | | 156 | | 171 | | 160 | | 32.1 | | 33.1 | | 31.4 | | 191.8 | | 191.5 | | 191.9 | |  | |
| 20 | 31.1 | 29.6 | | 29.9 | | 28 | | 28 | | 27 | | 111 | | 97 | | 102 | | 19.1 | | 16.5 | | 17.1 | | 74.9 | | 71.2 | | 71.9 | |  | |
| 30 | 11.4 | 11.4 | | 9.8 | | 9 | | 11 | | 7 | | 82 | | 74 | | 77 | | 14.3 | | 13.2 | | 14.0 | | 27.4 | | 27.4 | | 23.5 | |  | |
| 40 | 2.6 | 2.9 | | 1.6 | | 0 | | 1 | | -1 | | 66 | | 61 | | 67 | | 12.5 | | 11.2 | | 12.7 | | 6.4 | | 6.9 | | 3.8 | |  | |
| 50 | -0.8 | -1.1 | | -1.6 | | -3 | | -3 | | -3 | | 58 | | 55 | | 60 | | 11.8 | | 11.1 | | 11.8 | | -1.9 | | -2.7 | | -4.0 | | \*\* | |
| 2 | 10 | 59.9 | 59.6 | | 59.8 | | 54 | | 55 | | 54 | | 132 | | 126 | | 116 | | 24.9 | | 24.8 | | 23.2 | | 144.3 | | 143.4 | | 144.0 | |  | |
| 20 | 31.2 | 28.9 | | 29.9 | | 28 | | 26 | | 29 | | 103 | | 90 | | 93 | | 18.8 | | 16.0 | | 16.2 | | 75.2 | | 69.5 | | 71.9 | |  | |
| 30 | 13.4 | 14.2 | | 13.1 | | 14 | | 14 | | 13 | | 85 | | 76 | | 83 | | 15.0 | | 14.4 | | 14.3 | | 32.4 | | 34.2 | | 31.6 | |  | |
| 40 | 3.4 | 4.3 | | 3.7 | | 0 | | 2 | | 1 | | 69 | | 63 | | 63 | | 12.8 | | 11.3 | | 12.1 | | 8.3 | | 10.4 | | 8.9 | |  | |
| 50 | -0.1 | -0.8 | | -0.9 | | -3 | | -4 | | -3 | | 56 | | 52 | | 58 | | 11.9 | | 10.9 | | 11.5 | | -0.4 | | -1.9 | | -2.2 | | \*\* | |
| 3 | 10 | 56.7 | 54.5 | | 56.3 | | 52 | | 50 | | 52 | | 128 | | 105 | | 106 | | 23.7 | | 20.6 | | 22.1 | | 136.7 | | 131.2 | | 135.5 | |  | |
| 20 | 24.9 | 21.2 | | 23.4 | | 24 | | 19 | | 23 | | 102 | | 74 | | 89 | | 16.5 | | 13.8 | | 15.4 | | 59.9 | | 51.2 | | 56.4 | |  | |
| 30 | 12.0 | 11.1 | | 11.5 | | 10 | | 9 | | 10 | | 87 | | 74 | | 77 | | 14.4 | | 13.1 | | 13.4 | | 28.9 | | 26.7 | | 27.8 | |  | |
| 40 | 4.1 | 5.0 | | 4.8 | | 0 | | 3 | | 2 | | 68 | | 64 | | 63 | | 12.7 | | 11.4 | | 11.6 | | 10.0 | | 12.0 | | 11.5 | |  | |
| 50 | 0.2 | -0.1 | | -0.1 | | -2 | | -3 | | -3 | | 59 | | 53 | | 56 | | 11.9 | | 11.1 | | 11.4 | | 0.5 | | -0.3 | | -0.2 | | \*\*\* | |
| 4 | 10 | 54.7 | 51.4 | | 53.6 | | 49 | | 49 | | 50 | | 133 | | 97 | | 110 | | 23.1 | | 18.9 | | 21.1 | | 131.8 | | 123.7 | | 129.1 | |  | |
| 20 | 22.5 | 17.6 | | 20.7 | | 22 | | 15 | | 19 | | 104 | | 68 | | 82 | | 16.2 | | 12.4 | | 14.1 | | 54.2 | | 42.4 | | 49.8 | |  | |
| 30 | 9.5 | 8.1 | | 9.1 | | 8 | | 6 | | 6 | | 75 | | 68 | | 71 | | 13.4 | | 11.9 | | 12.8 | | 22.9 | | 19.4 | | 21.9 | |  | |
| 40 | 3.4 | 3.9 | | 4.0 | | 0 | | 1 | | 0 | | 66 | | 60 | | 62 | | 12.4 | | 11.1 | | 11.8 | | 8.2 | | 9.4 | | 9.5 | |  | |
| 50 | 0.4 | 0.5 | | 0.6 | | -2 | | -3 | | -2 | | 61 | | 56 | | 58 | | 11.7 | | 11.3 | | 11.3 | | 1.0 | | 1.3 | | 1.4 | | \*\* | |

**Appendix C. Identification of peaks in accelerometery data from the harness group.**

