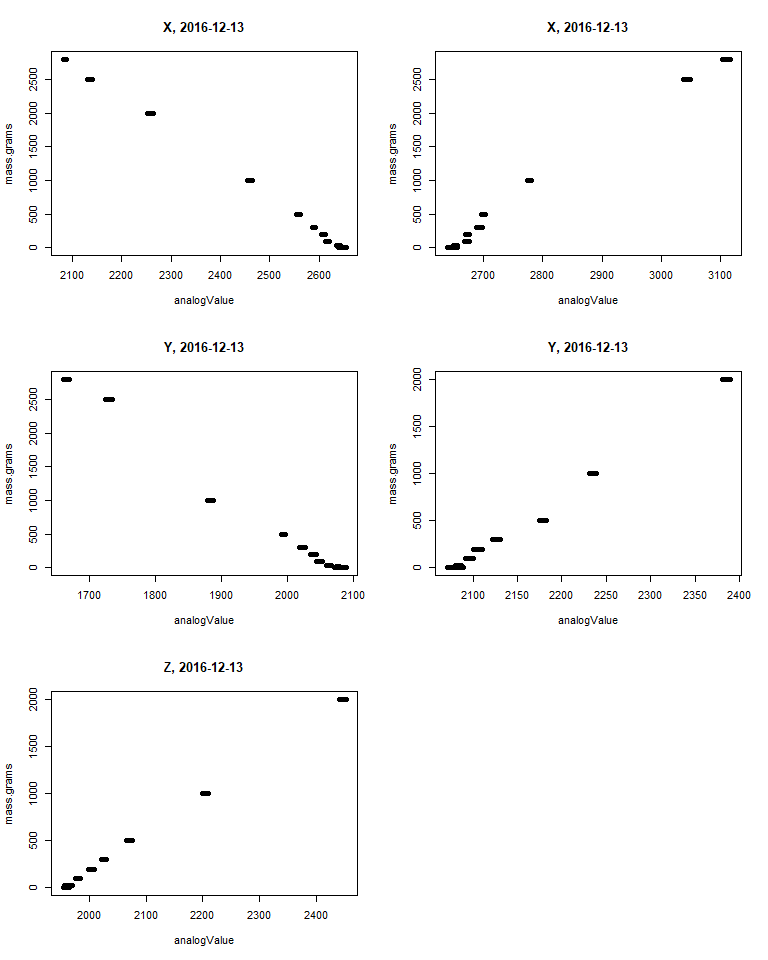
Limpet force meter analysis code

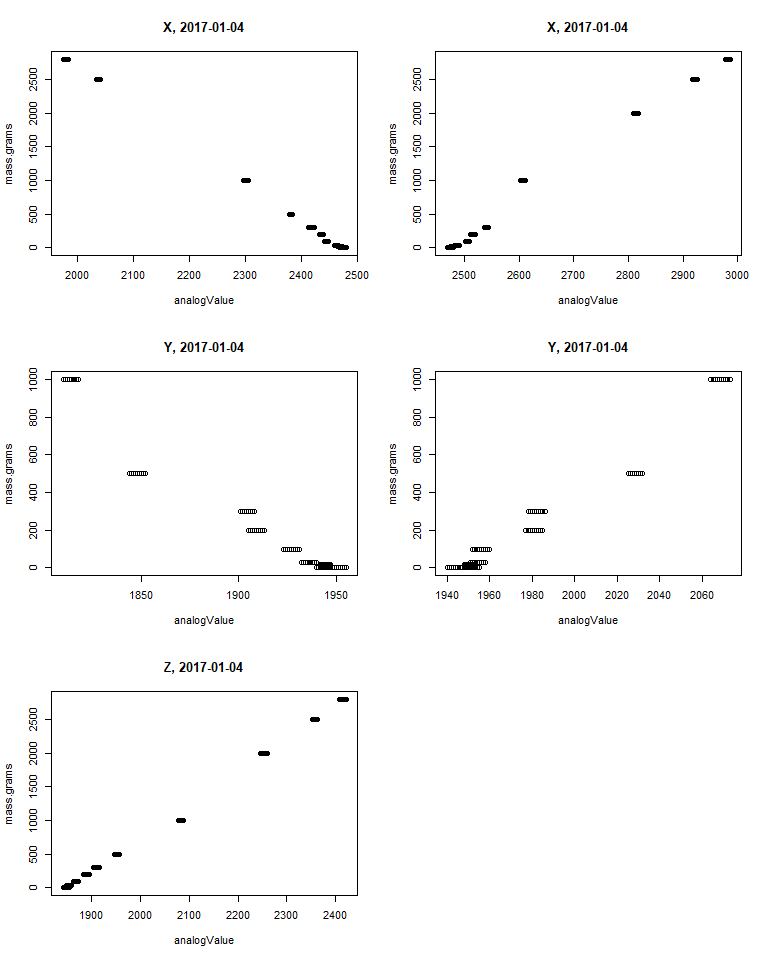
# library(circular) # Call this as needed below, since it masks mean() and sd()  
library(RColorBrewer)   
library(plotrix)  
library(RANN) # for nn2 nearest neighbor search function  
library(png)

The calibration data for the positive Y-axis on 2016-12-14 appear to be no good in the summary calibration file. The connector for this transducer axis was not functional. In order to still use the data from the 2016-12-15 trial, we can instead use the same calibration from 2016-12-13, which is the closest previous calibration. For some of the other calibration events, data for certain masses appear to be erroneous (possibly due to the wrong mass value being entered during calibration). The code removes potentially spurious calibration data points, and the calibration data that end up being used in the analysis are plotted below.

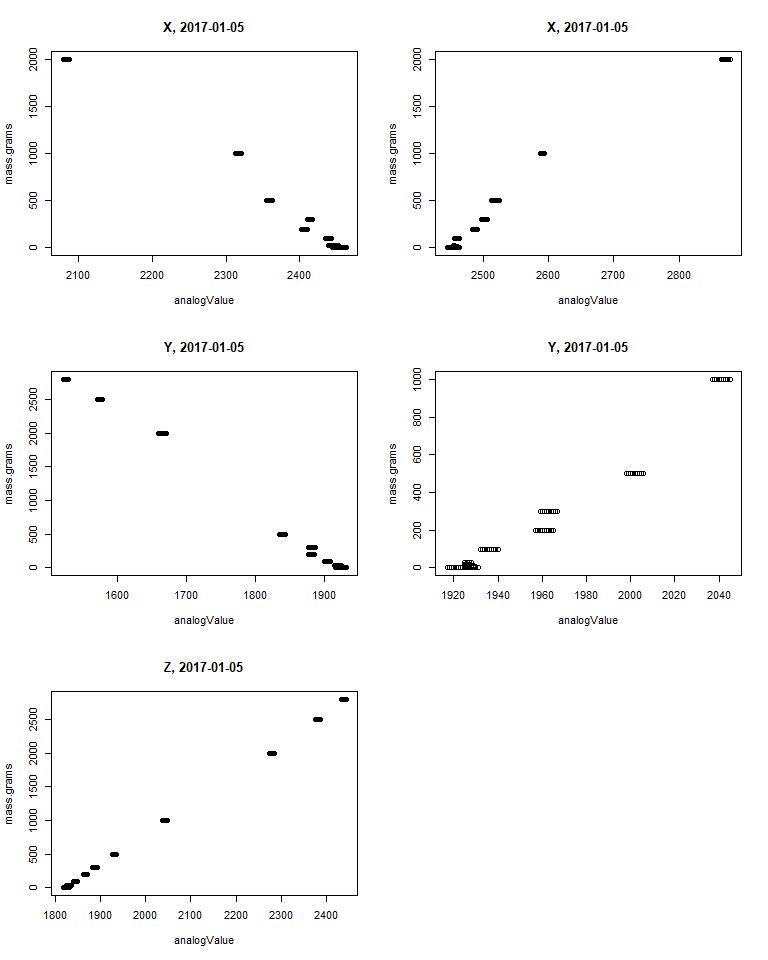
Note that the April 2016 trial data should not be analyzed, as the z-axis was not working. For the May 2016 trials, the closest available calibration data were from Apr 20 2016, so that calibration is used. The raw data from that calibration aren’t available currently, so we have to use the summary calibration data (means of the analog output value at each mass).



Calibration data from 2016-12-13



Calibration data from 2016-01-04



Calibration data from 2017-01-05

## [1] "CAL files raw data"   
## [2] "CalibrationFiles\_Apr202016.csv"   
## [3] "CalibrationFiles\_Dec132016.csv"   
## [4] "CalibrationFiles\_Jan42017.csv"   
## [5] "CalibrationFiles\_Jan52017.csv"   
## [6] "Denny\_Blanchette\_2000\_tenacity\_data"  
## [7] "Events\_classified\_20180213.csv"   
## [8] "Events\_classified\_20200102.csv"   
## [9] "Events\_picker\_output\_20180213.csv"   
## [10] "ForceMeterData\_Apr262016.csv"   
## [11] "ForceMeterData\_Dec142016.csv"   
## [12] "ForceMeterData\_Dec152016.csv"   
## [13] "ForceMeterData\_Jan52017.csv"   
## [14] "ForceMeterData\_Jan62017.csv"   
## [15] "ForceMeterData\_May182016.csv"   
## [16] "ForceMeterData\_May192016.csv"   
## [17] "Pound\_ForceData\_Final.csv"

The relevant calibration file for the May 2016 trials is the Apr202016 file.

During the import process, the calibration files and force trial files are concatenated together into two data frames, calibs and forces, each with a Date column that can be used to separate different days. The data frame events contains the identified peck and push events, with dates and millisecond timestamps.

The goal is to go through each identified event and extract the X, Y, and Z-axis forces (which need to be estimated based on the associated calibration values). The events data frame currently only has the net euclidean norm (total for all 3 axes).

## DEFINTIONS

These definitions are based on Rachel’s email from 2018-02-06.

* A given force can only be assigned to one category (cannot be a push *and* peck)
* Forces discussed below refer to net Euclidean forces in 3 dimensions (norm).

### Peck:

* Peak magnitude: ≥ 2 N, and MUST BE greater than or equal to two times the magnitude of the force data points immediately before AND after a given point.
* Duration: Force > 2 N MUST BE sustained for ≤ 2 successive samples, giving a total event duration of less than 30 ms.
* Both the magnitude and duration conditions must be met in order for a force to be categorized as a Peck

### Push:

* Peak magnitude: ≥ 2 N, and may or may not be greater than or equal to two times the magnitude of the force before and after a given force data point
* Duration: Forces ≥ 2 N that do not meet the magnitude criteria for a Peck may be sustained for any amount of time
* Forces categorized as Pushes do not meet conditions of Peck and Touch

### Touch:

* Magnitude: < 2 N (e.g. the bird seems to be playing with the ‘limpet’ mimic rather than actively attempting to remove it)
* We are not considering ‘Touches’ in our force meter analyses

Additional clarification, from Rachel in email on 2018-02-06: “Secondly, had event #3 been an actual force produced by the bird, we did classify these events as a peck because had considered a peck to be a force that was exerted over one or two sampling intervals. We did this because there were instances when the bird produced two forces in quick succession that created a distinct force peak on the read outs (such as in your Limpet\_force\_meter\_analysis, figure 2016-12-14, 621.47s, push). In this case, we classified both of the peaks in that example as pecks because, when the forces were lumped together, the magnitude of the first and second forces were twice the magnitude of the forces before or after it (presumably in this case those forces were 0 N). So even though those two forces are not distinct peaks, in an example like this, we lumped them together as one peak.”

## Picking pecks and pushes

I wrote an interactive function (PushPeckPickFunction()) to let the user pick a trial date and go through the raw time series data and attempt to identify potential pecks and pushes. The script has the user first identify a period of at least 8 samples (80 milliseconds) where the baseline signal appears stable, and then the user clicks on each peak above the 2N threshold outlined above. Because the sensors tended to drift and take new baseline values, particularly after big hits by the bird, the user is identifying a new baseline for each peak or group of peaks that happen in quick succession and appear to share a common baseline value. The output of the function peakChooser() is a data frame that contains a row from the original forces data frame for each identified peak. As a result, the time in milliseconds (Time.msec), the raw X, Y, Z values (X.N,Y.N,Z.N, units of Newtons), calibrated forces in the X, Y, and Z axes (X.N.off, Y.N.off,Z.N.off, units of Newtons), the euclidean norm of all 3 axes (Norm, units of Newtons), and the time stamp of the chosen baseline value (BaselineTime.msec) are available for each peak event. These data could be used to relocate a chunk of the raw time series around each peak event for further analysis.

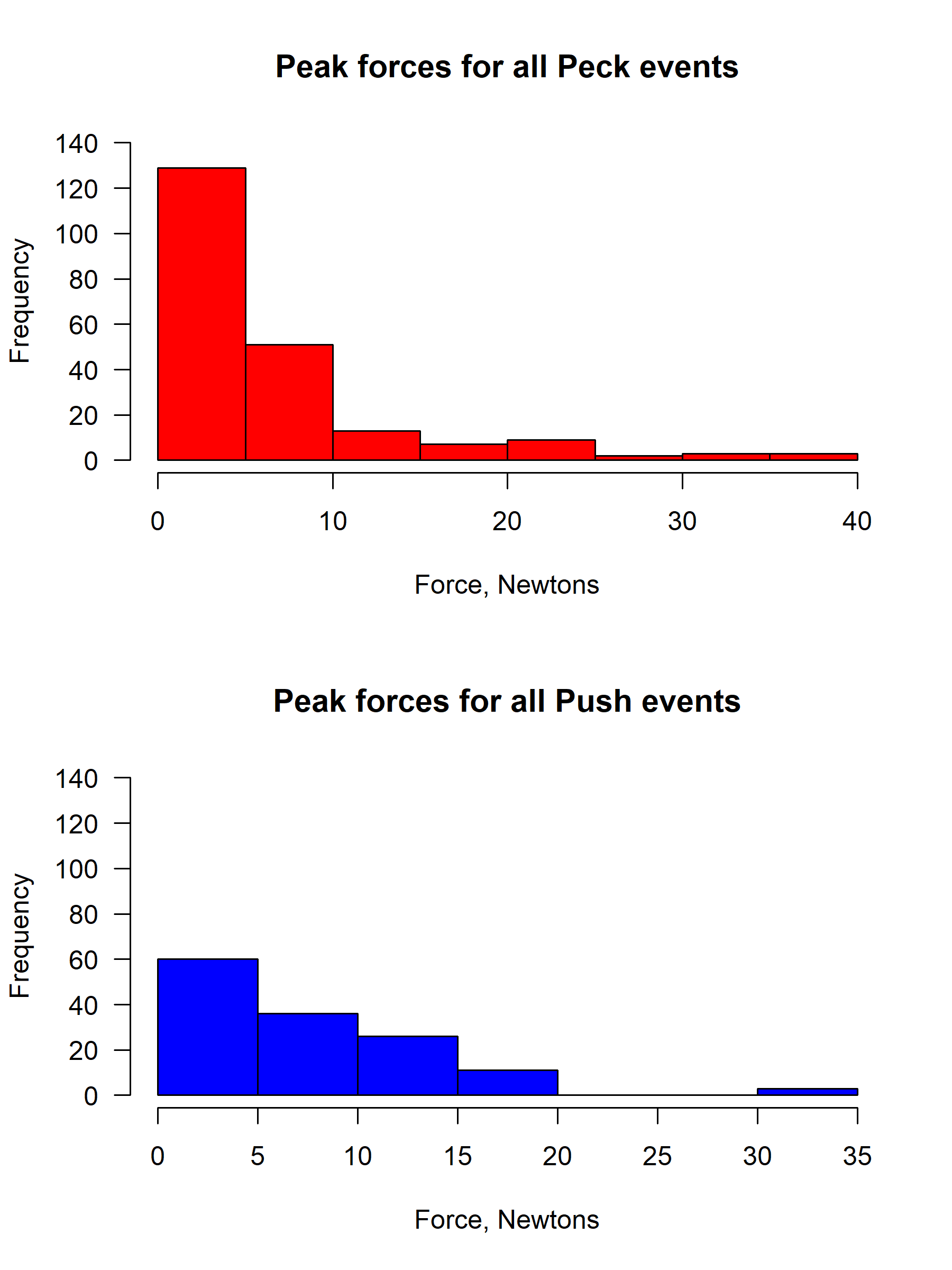
# Classifying peaks vs. pushes

The output from the peakChooser() function was saved to a csv file called Events\_picker\_output\_20180213.csv. The data in that file next need to be processed to determine if each event was a peck or a push according to the criteria outlined above.

The code defines a function peakPushAlgo() to classify each peak event as either a push or peck, when an sample force greater than 2 Newtons was identified. The function peckpushClassify() then cycles through all identified events and classifies them. The code in peakpushClassify() also determines the duration of each event, based on the time the force spent above the 2 Newton threshold during that event. Because the raw data were sampled at 10 millisecond intervals, a single peak force above 2 Newtons (peck) will have a maximum duration of 20 ms. That is the time it takes to go from ~0 N to >2 N and back to ~0 N over the course of 3 samples. However, based on our earlier definition of a Peck (1 OR 2 sample forces above 2N), we also include events where the force was above the 2 N threshold for 2 samples in a row, which means the force was above 2 N for at most 30 ms, which is the interval between 4 sample points. Thus peck events will have a duration recorded in the output file of either 20 ms (single sample above 2 N, which takes a minimum of two 10 ms intervals to be recorded by the transducer) or 30 ms (2 samples above 2 N, which takes a minimum of three 10 ms intervals to be recorded by the transducer).

For push events, the duration of time the force is >2 N should end up longer than 20 ms, where 20 ms encompasses 3 sampling time points, and durations longer than 20 ms encompass 4 or more sampling time points. The output of peakpushClassify() is a data frame similar to the input events data frame, but with four new columns added on, PeckPush, Duration.msec, StartPeak.msec, and EndPeak.msec. The latter two columns list the time stamp in milliseconds where the algorithm declared the start and end of a given event (the force exceeding the 2 Newton threshold). If an event in the events data frame does not meet the critera for a peck or a push, these new columns will contain NA.

The results were saved to a csv file Events\_classified\_20180213.csv.



## Summary data for all identified events. Values are force in Newtons.

## Max Min Mean SD Median N  
## Peck 37.36 2.01 6.86 7.00 4.41 217  
## Push 31.89 2.03 7.79 5.97 6.04 136

## -----------------------------------

## Summary data for the highest 10% of events. Values are force in Newtons.

## Mean SD N  
## Peck 24.90 7.14 22  
## Push 20.93 5.80 14

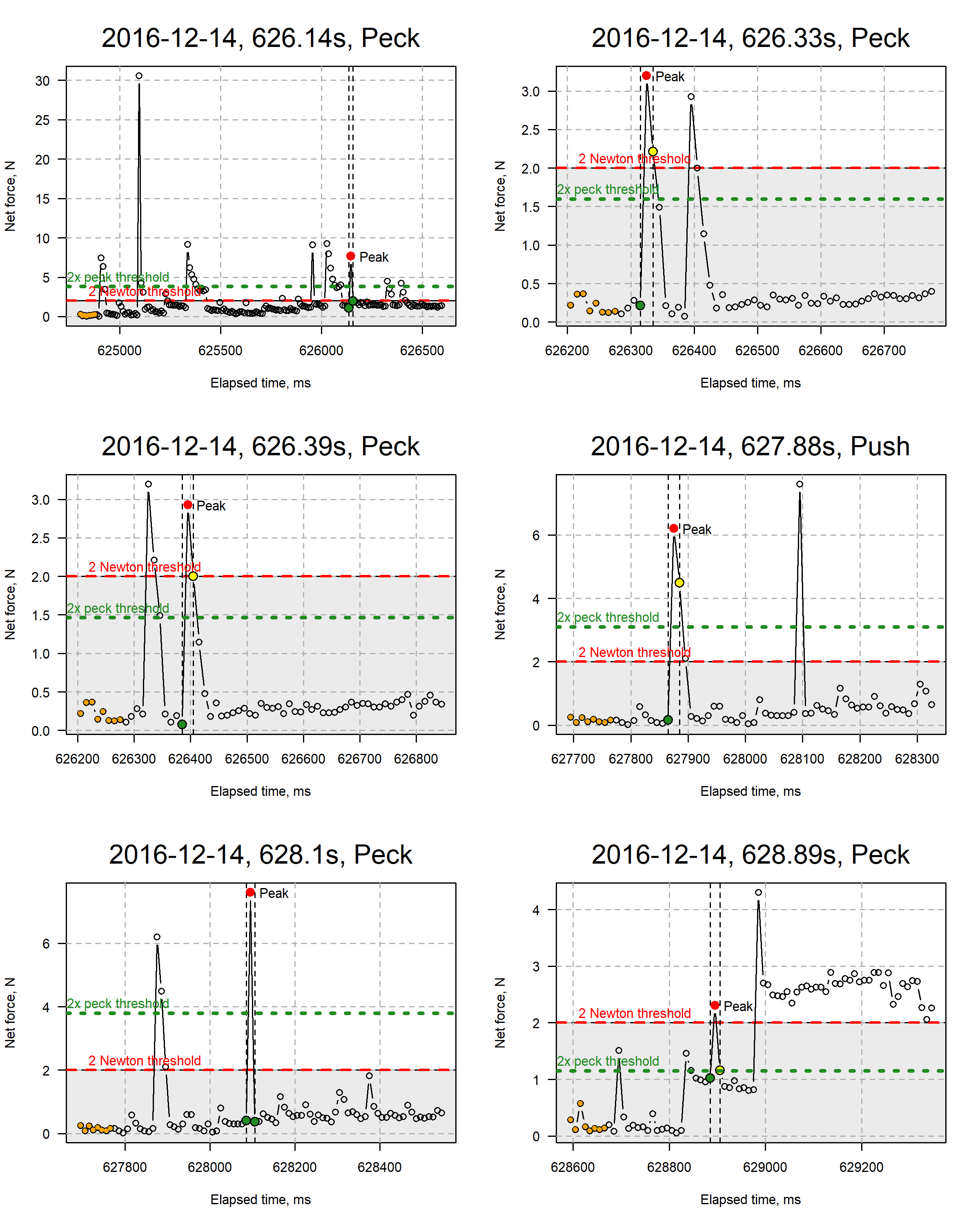
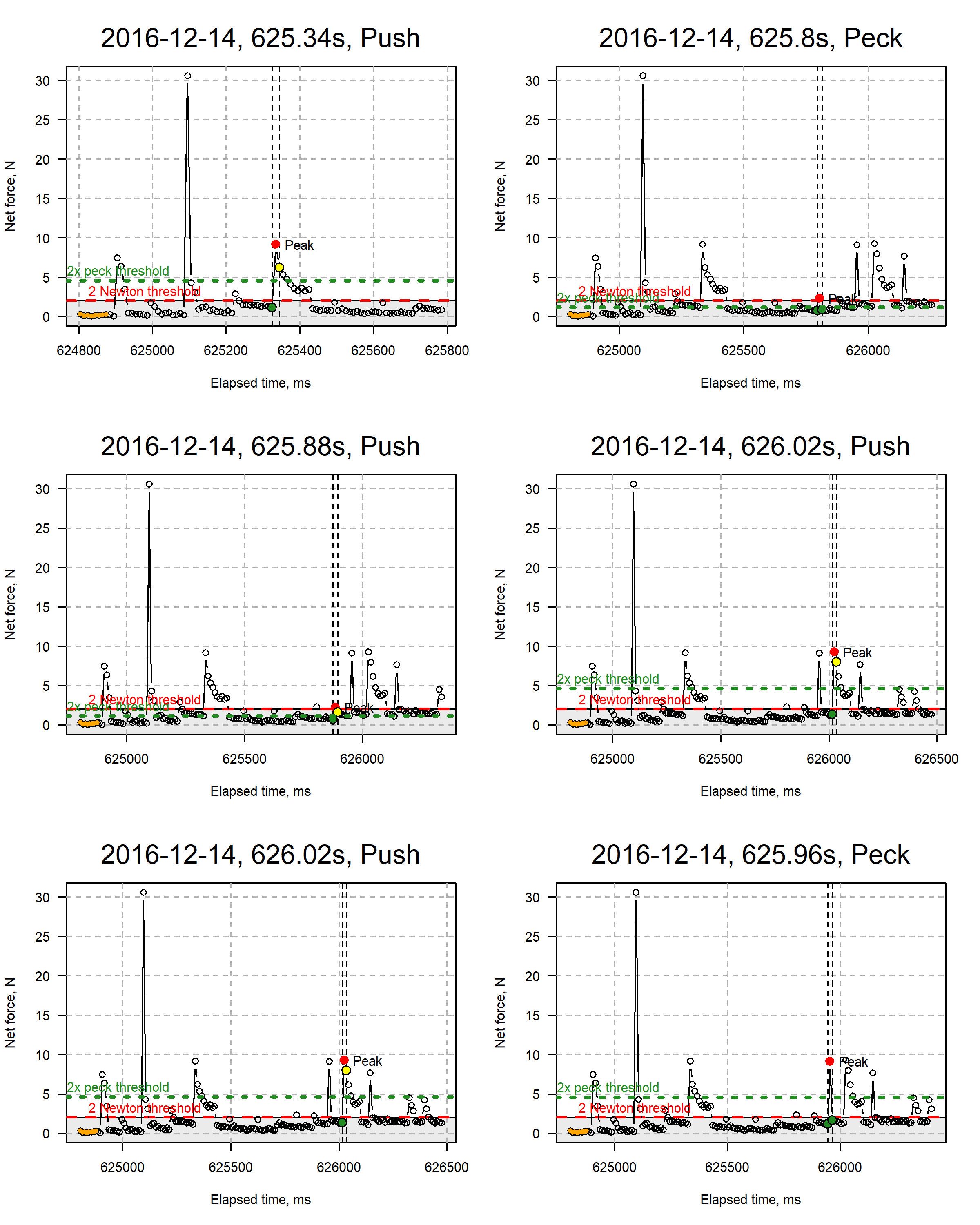
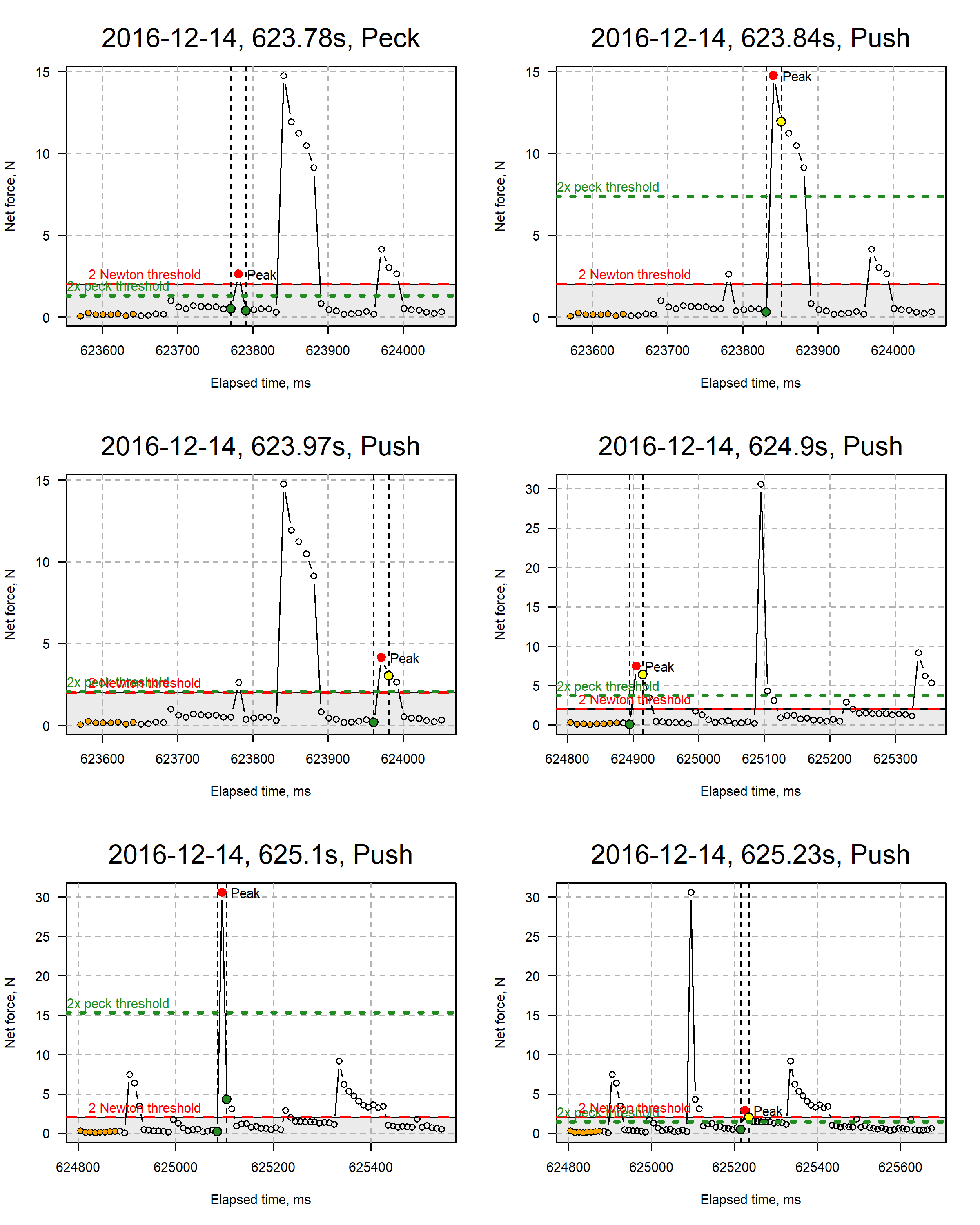
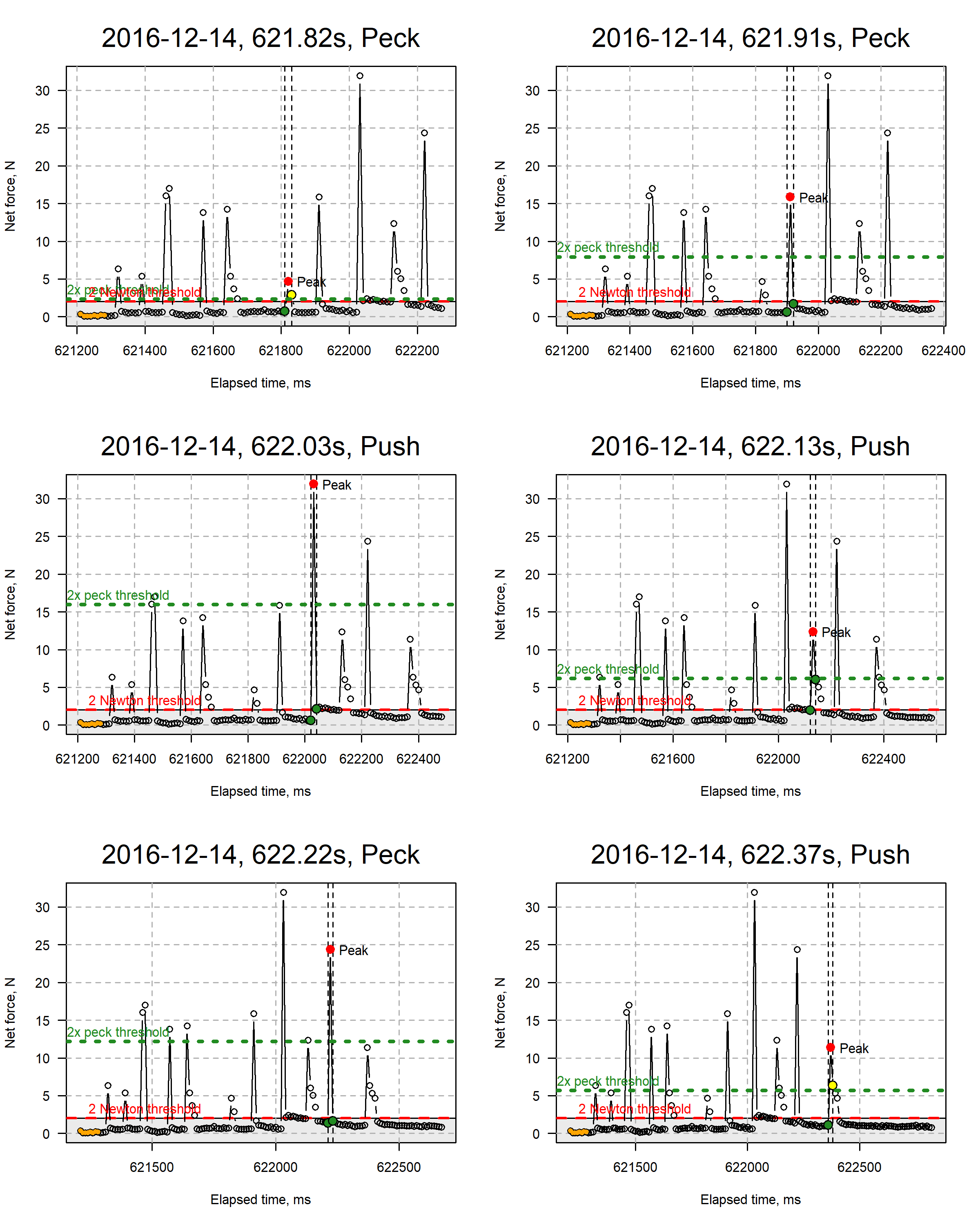
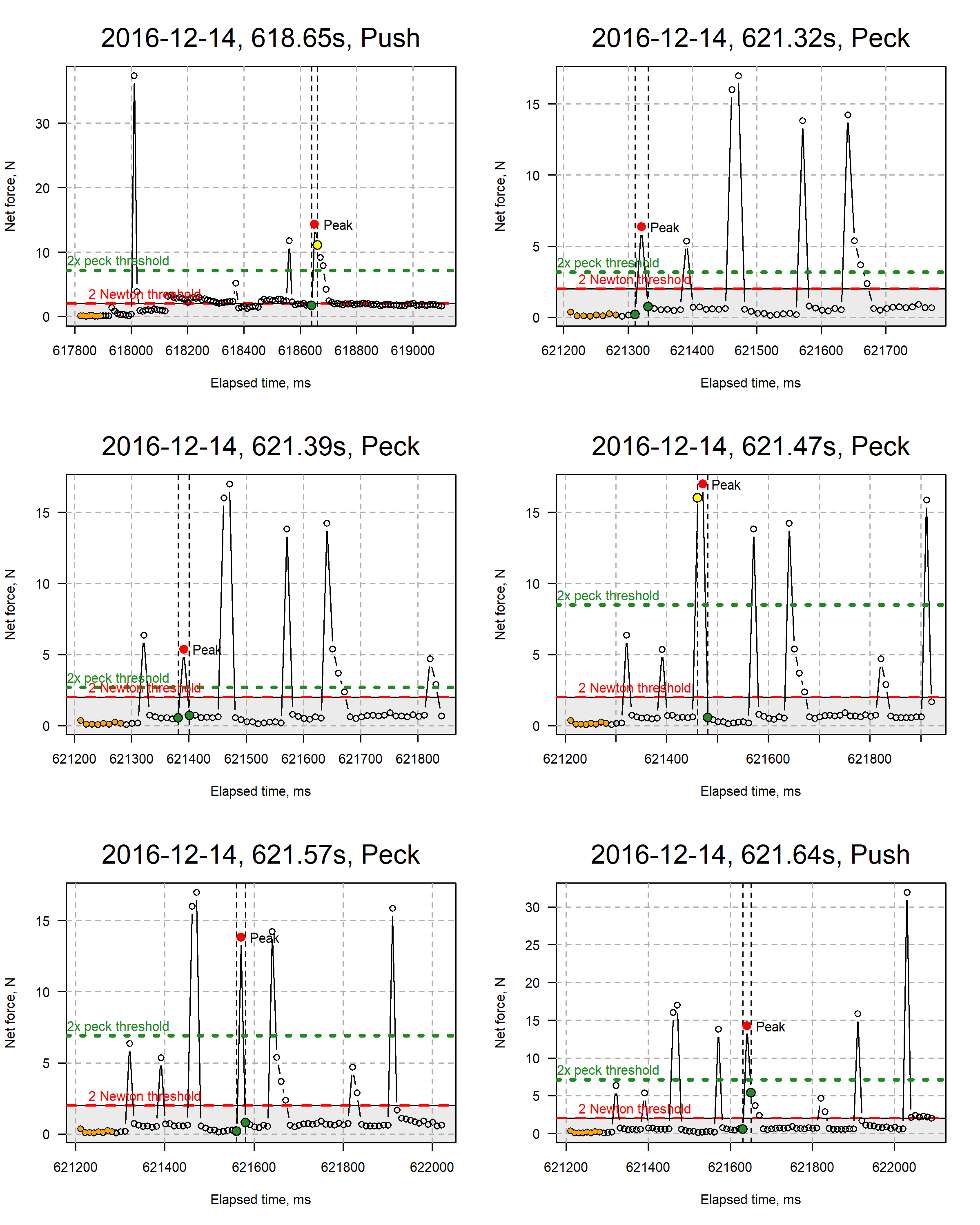
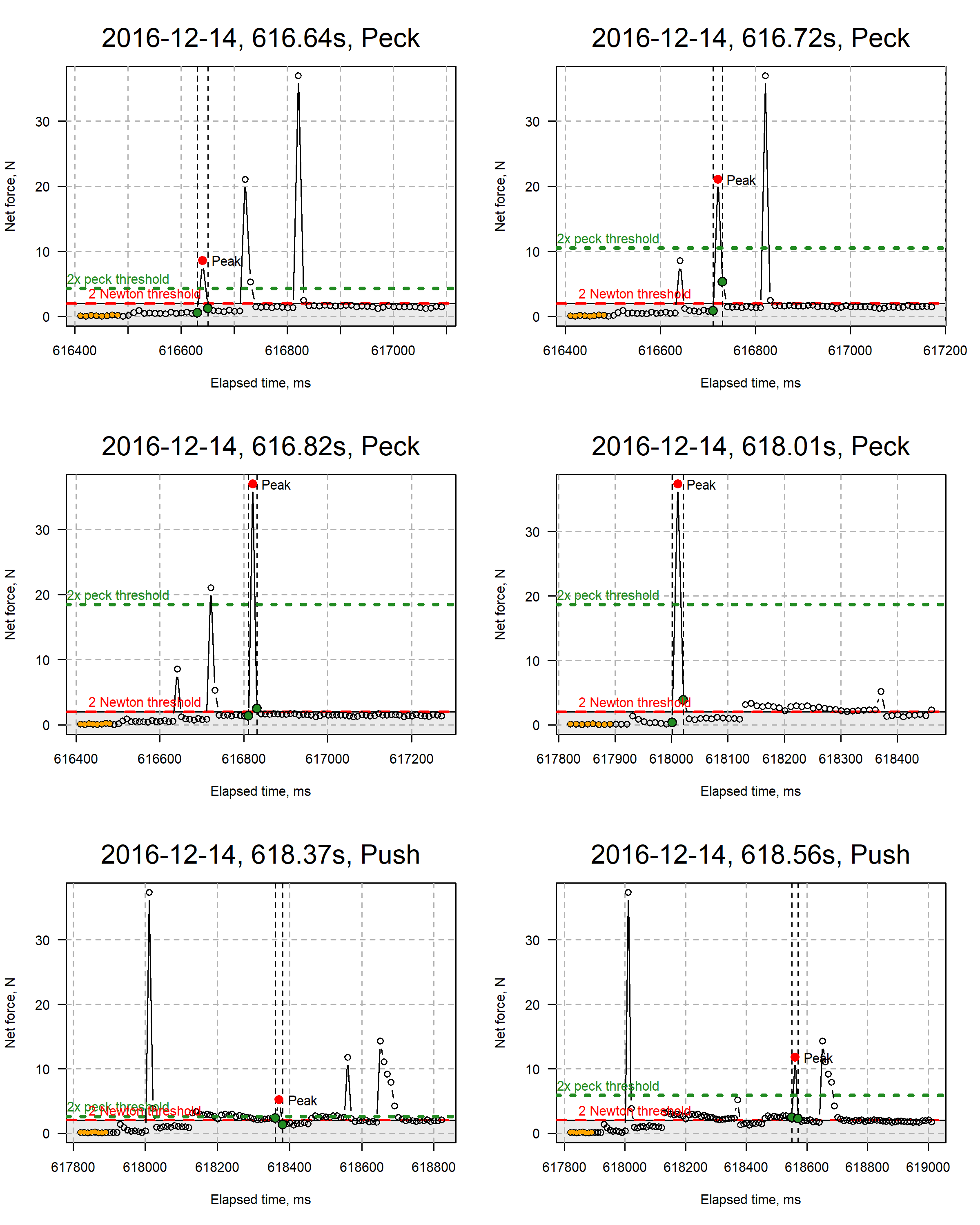
Below are some example classified Pecks and Pushes. The figures have guidelines showing where the thresholds are for classification as a peck or push. These are not all of the events picked out.

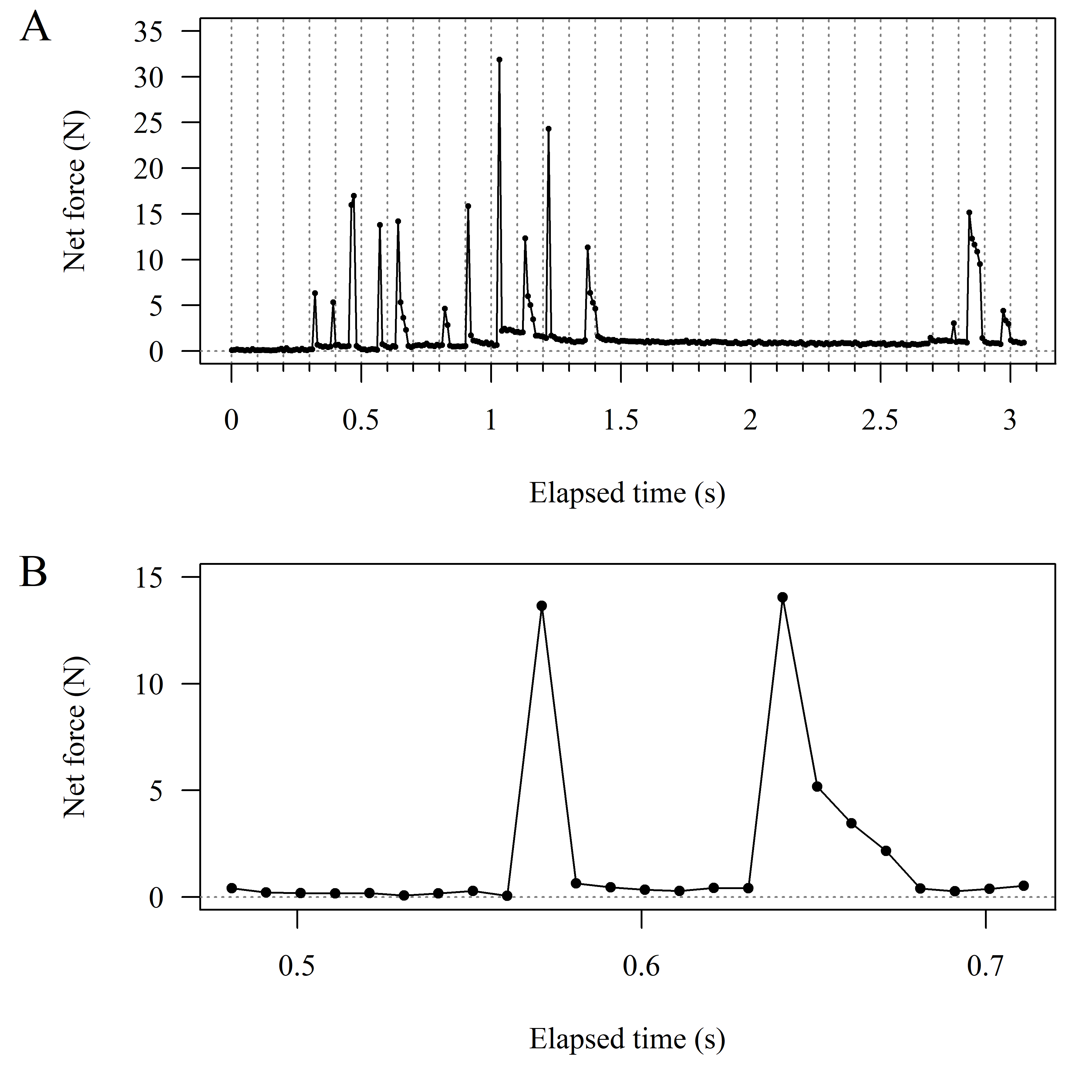
##   
## Fraction of pecks greater than 14 Newtons net force (3 dimensions)

## [1] 0.1152

##   
## Fraction of pushes greater than 14 Newtons net force (3 dimensions)

## [1] 0.1324





Examples of net forces exerted by the captive bird on the force transducer. Data from 2016-12-14 at 621.5 sec elapsed

Median and mean interval (milliseconds) between strikes (less than 10 seconds apart), on each sampling date.

|  |  |  |  |
| --- | --- | --- | --- |
| Date | Median.msec | Mean.msec | SampleSize |
| 2016-12-14 | 110 | 286.2700 | 100 |
| 2016-12-15 | 150 | 577.7419 | 31 |
| 2016-05-18 | 100 | 484.1429 | 21 |
| 2016-05-19 | 110 | 445.9684 | 95 |
| 2017-01-05 | 110 | 221.0526 | 19 |
| 2017-01-06 | 80 | 181.0328 | 61 |

Median and mean interval (milliseconds) between strikes, for all events spaced less than 10 seconds apart. Each event is defined as a series of strikes that occured no more than 10 seconds apart. The number of strikes in each attack is given, along with the attack number identifier.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Date | Median.msec | Mean.msec | SampleSize | Attack |
| 2016-12-14 | 120 | 331.1356 | 59 | 1 |
| 2016-12-14 | 100 | 242.4000 | 25 | 2 |
| 2016-12-14 | 105 | 189.3750 | 16 | 3 |
| 2016-12-15 | 190 | 3361.5000 | 8 | 4 |
| 2016-12-15 | 120 | 120.0000 | 2 | 5 |
| 2016-12-15 | 390 | 720.0000 | 8 | 6 |
| 2016-12-15 | 125 | 142.5000 | 4 | 7 |
| 2016-12-15 | 275 | 430.0000 | 10 | 8 |
| 2016-05-18 | 145 | 145.0000 | 2 | 9 |
| 2016-05-18 | 385 | 1511.0000 | 4 | 10 |
| 2016-05-18 | 90 | 133.3333 | 3 | 11 |
| 2016-05-18 | 100 | 502.6000 | 5 | 12 |
| 2016-05-18 | 235 | 235.0000 | 2 | 13 |
| 2016-05-18 | 90 | 90.0000 | 5 | 14 |
| 2016-05-19 | 110 | 521.2667 | 60 | 15 |
| 2016-05-19 | 100 | 100.0000 | 2 | 16 |
| 2016-05-19 | 110 | 379.6400 | 25 | 17 |
| 2016-05-19 | 110 | 175.0000 | 8 | 18 |
| 2017-01-05 | 100 | 122.0000 | 5 | 19 |
| 2017-01-05 | 115 | 256.4286 | 14 | 20 |
| 2017-01-06 | 80 | 160.5652 | 23 | 21 |
| 2017-01-06 | 250 | 198.0000 | 5 | 22 |
| 2017-01-06 | 80 | 192.7273 | 33 | 23 |

# Peck/Push direction

We can use the 3-dimensional force data to estimate the direction/angle that the bird attacked the mimic limpet at.

## Strongest overall force in horizontal plane (this was a peck), Newtons

## [1] 36.62813

##   
## Strongest push force in horizontal plane, Newtons

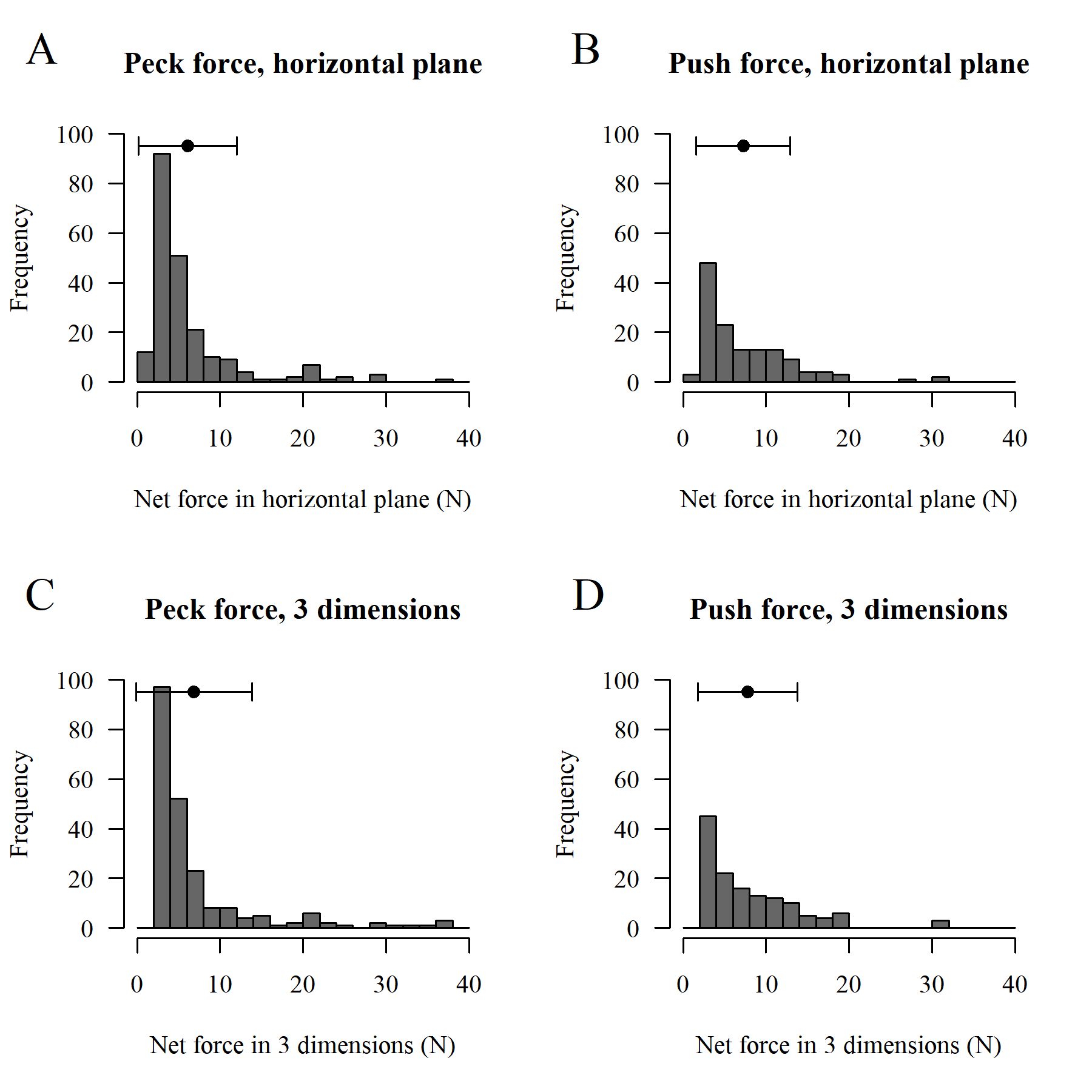
## [1] 30.55752

##   
## Fraction of horizontal pecks greater than 14 Newtons

## [1] 0.08294931

##   
## Fraction of horizontal pushes greater than 14 Newtons

## [1] 0.1029412



Histogram of forces in the horizontal plane (A,B) and three dimensions (C,D), classified as pecks or pushes. Left column shows events classified as pecks (n = 217), right column shows events classified as pushes (n = 136). Points and error bars represent the mean +/- 1 SD.

* For horizontal pecks, the mean + 1SD was 6.082 + 5.916. Sample size was 217.
* For horizontal pushes, the mean + 1SD was 7.229 + 5.67. Sample size was 136.
* For pecks in 3 dimensions, the mean + 1SD was 6.862 + 7.001. Sample size was 217.
* For pushes in 3 dimensions, the mean + 1SD was 7.787 + 5.971. Sample size was 136.

## Warning: package 'circular' was built under R version 3.6.2

## Package 'circular', 0.4-93 (2017-06-26). Type 'help(Circular)' for summary information.   
## Please report any bug or comments to Claudio Agostinelli <claudio.agostinelli@unitn.it>

##   
## Attaching package: 'circular'

## The following objects are masked from 'package:stats':  
##   
## sd, var

library(circular, quietly = TRUE)

## Warning: package 'circular' was built under R version 3.6.2

## Package 'circular', 0.4-93 (2017-06-26). Type 'help(Circular)' for summary information.   
## Please report any bug or comments to Claudio Agostinelli <claudio.agostinelli@unitn.it>

##   
## Attaching package: 'circular'

## The following objects are masked from 'package:stats':  
##   
## sd, var

# Summary stats for only the downward-directed strikes (n=226)  
# We are subtracting 180 here just to make the numbers come out as positive  
# values representing angle \*below\* horizontal  
summary(vertAngle-180)

## n Min. 1st Qu. Median Mean 3rd Qu.   
## 226.00000 0.02952 4.29500 19.52000 20.54000 31.68000   
## Max. Rho   
## 75.04000 0.95770

mle.vonmises.bootstrap.ci(vertAngle-180)

## Bootstrap Confidence Intervals for Mean Direction and Concentration   
## Confidence Level: 95 %   
## Mean Direction: Low = 18.35 High = 22.73   
## Concentration Parameter: Low = 10.15 High = 14.36

#  
#  
# Summary stats for all strikes, downwards, horizontal, upwards (n=353)  
# Here again we subtract off 180 so that a \*downward\* directed force shows  
# up as a positive value representing angle \*below\* horizontal  
summary(af-180)

## n Min. 1st Qu. Median Mean 3rd Qu.   
## 353.0000 -80.8800 0.5238 4.4930 11.3600 24.9800   
## Max. Rho   
## 75.0400 0.9391

mle.vonmises.bootstrap.ci(af-180)

## Bootstrap Confidence Intervals for Mean Direction and Concentration   
## Confidence Level: 95 %   
## Mean Direction: Low = 9.34 High = 13.35   
## Concentration Parameter: Low = 7.22 High = 10.23

# Unload circular package to avoid interference with mean() and sd() functions  
detach('package:circular', unload=TRUE)

For the subset of strikes that were directed downwards towards the limpet (226), the mean strike angle was from 20.54 degrees above horizontal.

For all of the strikes (downwards, horizontal, or upwards, 353), the mean strike angle was from 11.36 degrees above horizontal.

## Package 'circular', 0.4-93 (2017-06-26). Type 'help(Circular)' for summary information.   
## Please report any bug or comments to Claudio Agostinelli <claudio.agostinelli@unitn.it>

##   
## Attaching package: 'circular'

## The following objects are masked from 'package:stats':  
##   
## sd, var

## Package 'circular', 0.4-93 (2017-06-26). Type 'help(Circular)' for summary information.   
## Please report any bug or comments to Claudio Agostinelli <claudio.agostinelli@unitn.it>

##   
## Attaching package: 'circular'

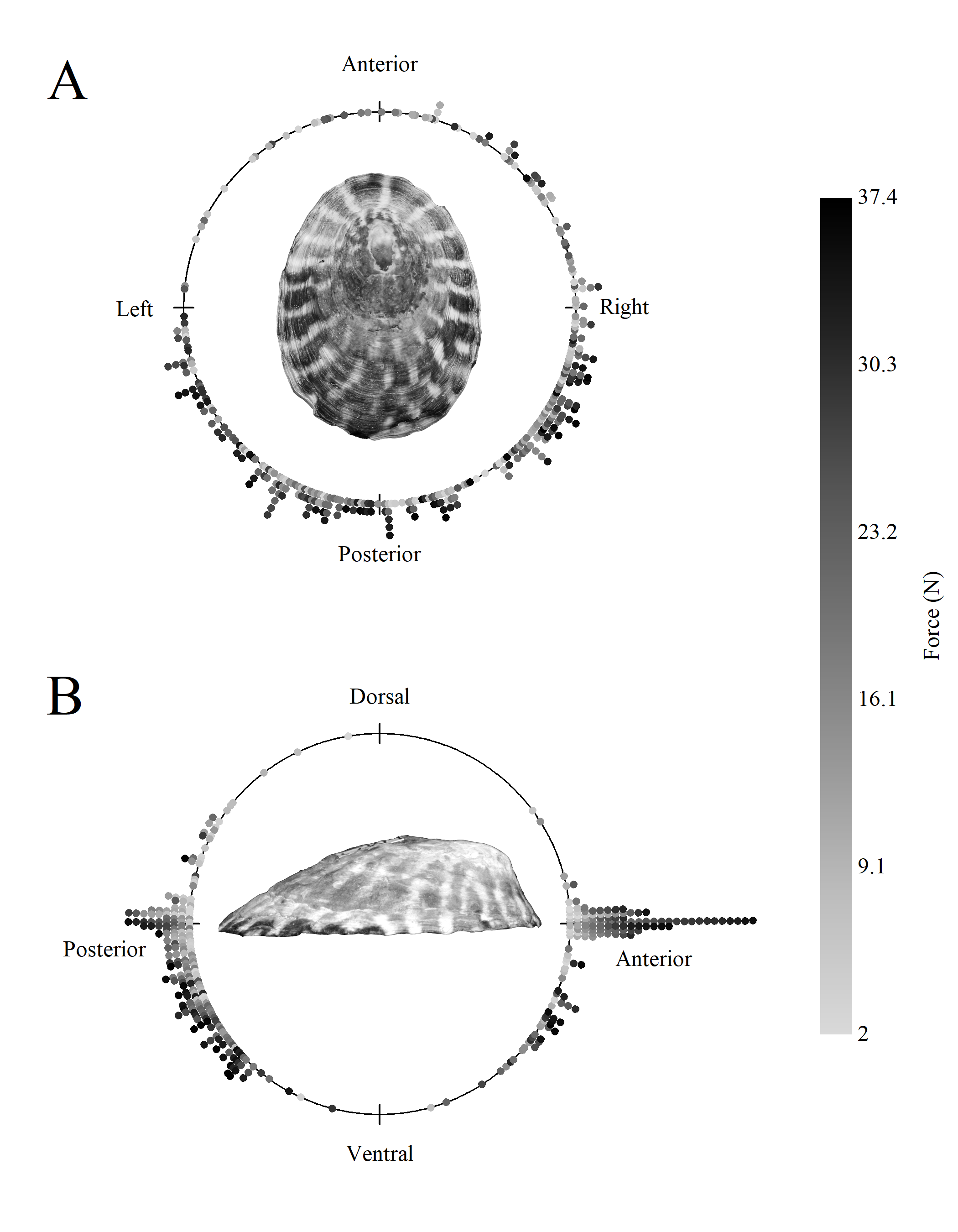
## The following objects are masked from 'package:stats':  
##   
## sd, var

## Package 'circular', 0.4-93 (2017-06-26). Type 'help(Circular)' for summary information.   
## Please report any bug or comments to Claudio Agostinelli <claudio.agostinelli@unitn.it>

##   
## Attaching package: 'circular'

## The following objects are masked from 'package:stats':  
##   
## sd, var

## [1] 1 2 3



Angular distribution of force vectors for pecks and pushes along the A) anterior-posterior and left-right axes and B) anterior-posterior and dorsal-ventral axes of the limpet mimic. Each point represents the resultant direction of a single strike event classified as a peck or push by the black oystercatcher during trials on 6 dates. Point colors indicate the net force in Newtons of the strike event.

## Package 'circular', 0.4-93 (2017-06-26). Type 'help(Circular)' for summary information.   
## Please report any bug or comments to Claudio Agostinelli <claudio.agostinelli@unitn.it>

##   
## Attaching package: 'circular'

## The following objects are masked from 'package:stats':  
##   
## sd, var

## Warning: package 'circular' was built under R version 3.6.2

## Package 'circular', 0.4-93 (2017-06-26). Type 'help(Circular)' for summary information.   
## Please report any bug or comments to Claudio Agostinelli <claudio.agostinelli@unitn.it>

##   
## Attaching package: 'circular'

## The following objects are masked from 'package:stats':  
##   
## sd, var

## Test of mean angle of attack in the horizontal plane for pecks vs pushes.

##   
## Call:  
## aov.circular(x = h, group = forceDir$PeckPush, method = "LRT")  
##   
##   
## Circular Analysis of Variance: Likelihood Ratio Test   
##   
## df: 1   
## ChiSq: 0.1143   
## p.value: 0.7353   
##

##   
##   
## Test of mean angle of attack in the vertical and   
##   
## anterior-posterior plane for pecks vs pushes.

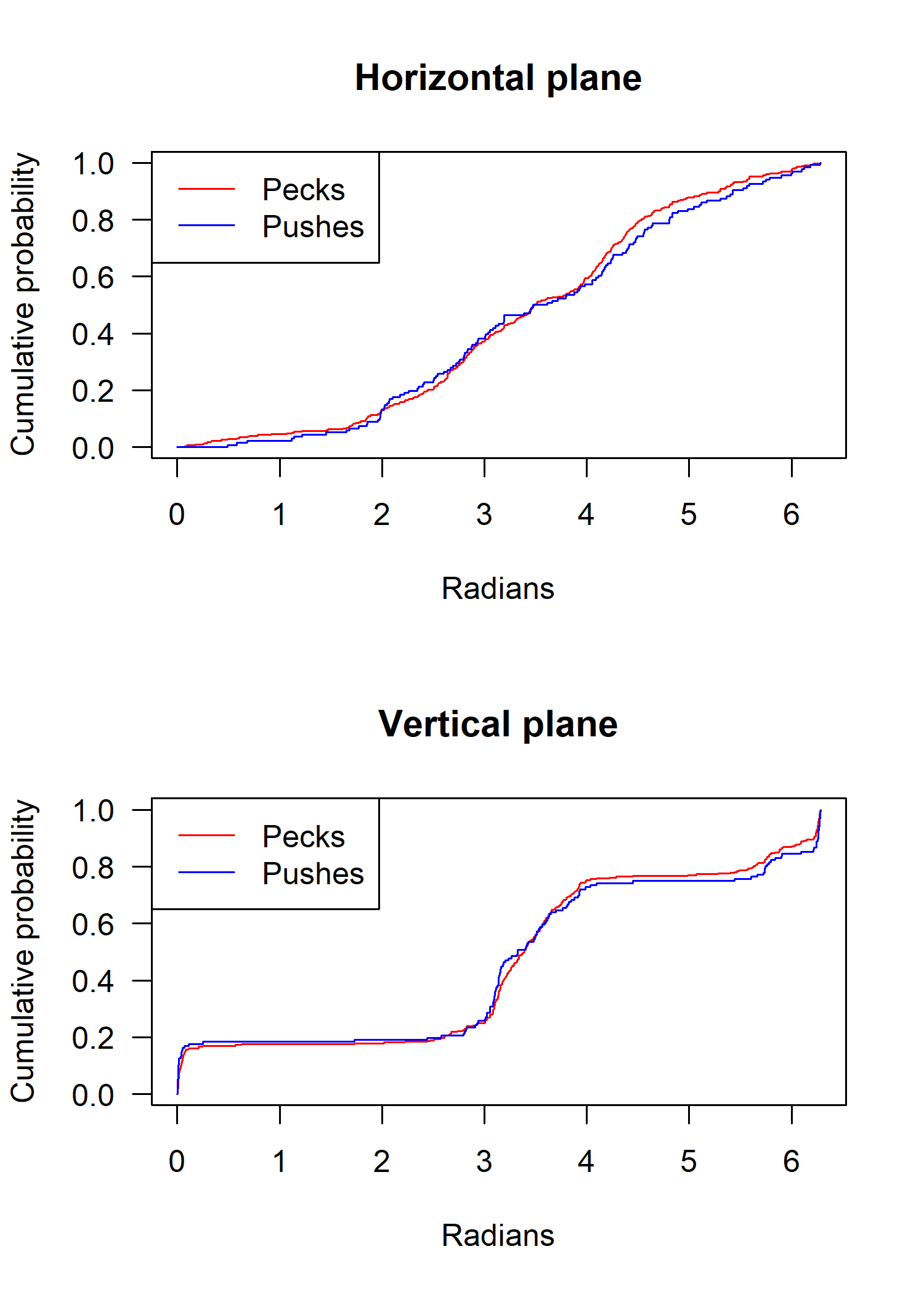
##   
## Call:  
## aov.circular(x = f, group = forceDir$PeckPush, method = "LRT")  
##   
##   
## Circular Analysis of Variance: Likelihood Ratio Test   
##   
## df: 1   
## ChiSq: 0.4219   
## p.value: 0.516   
##

## Warning: package 'circular' was built under R version 3.6.2

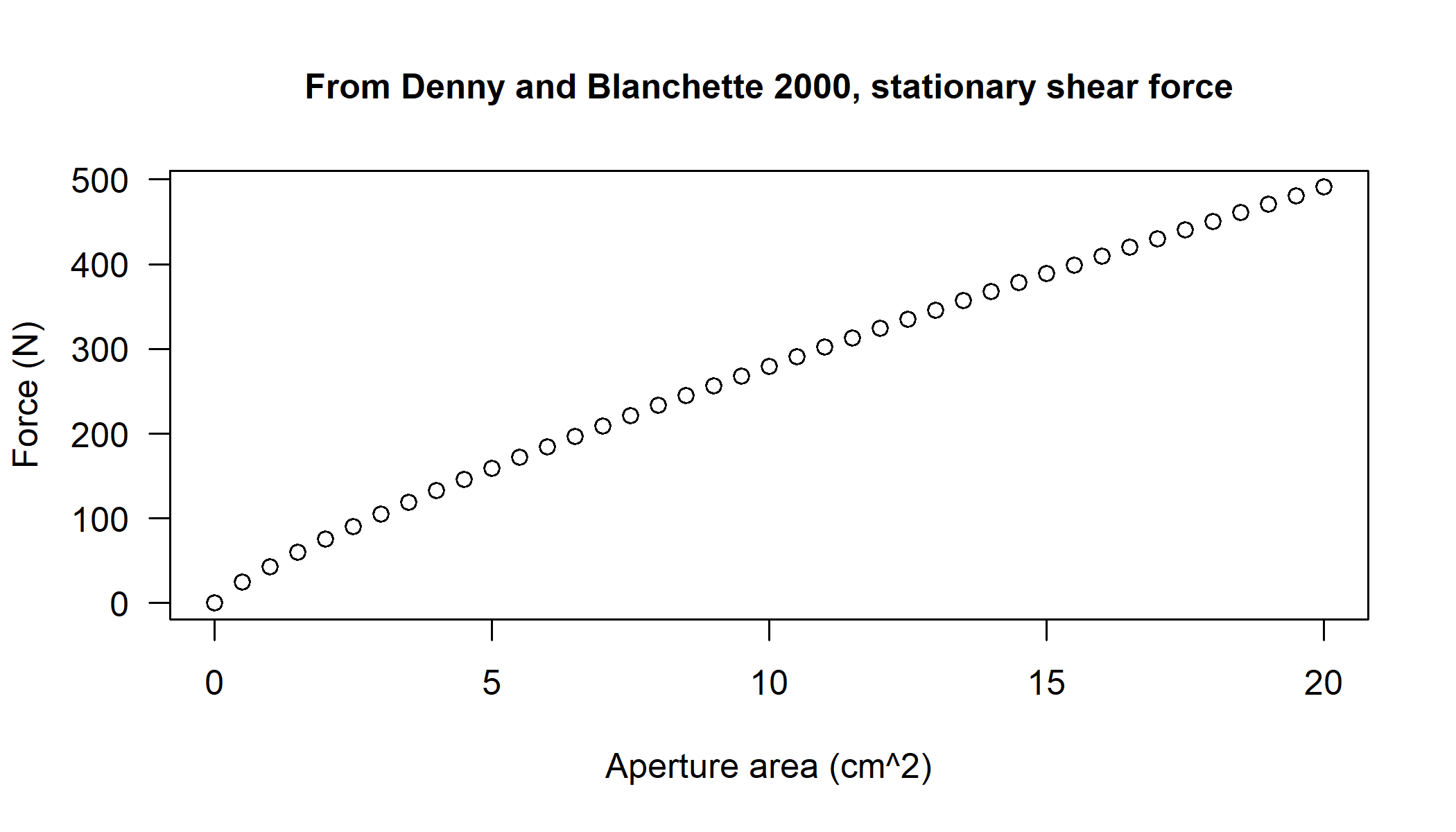
## Package 'circular', 0.4-93 (2017-06-26). Type 'help(Circular)' for summary information.   
## Please report any bug or comments to Claudio Agostinelli <claudio.agostinelli@unitn.it>

##   
## Attaching package: 'circular'

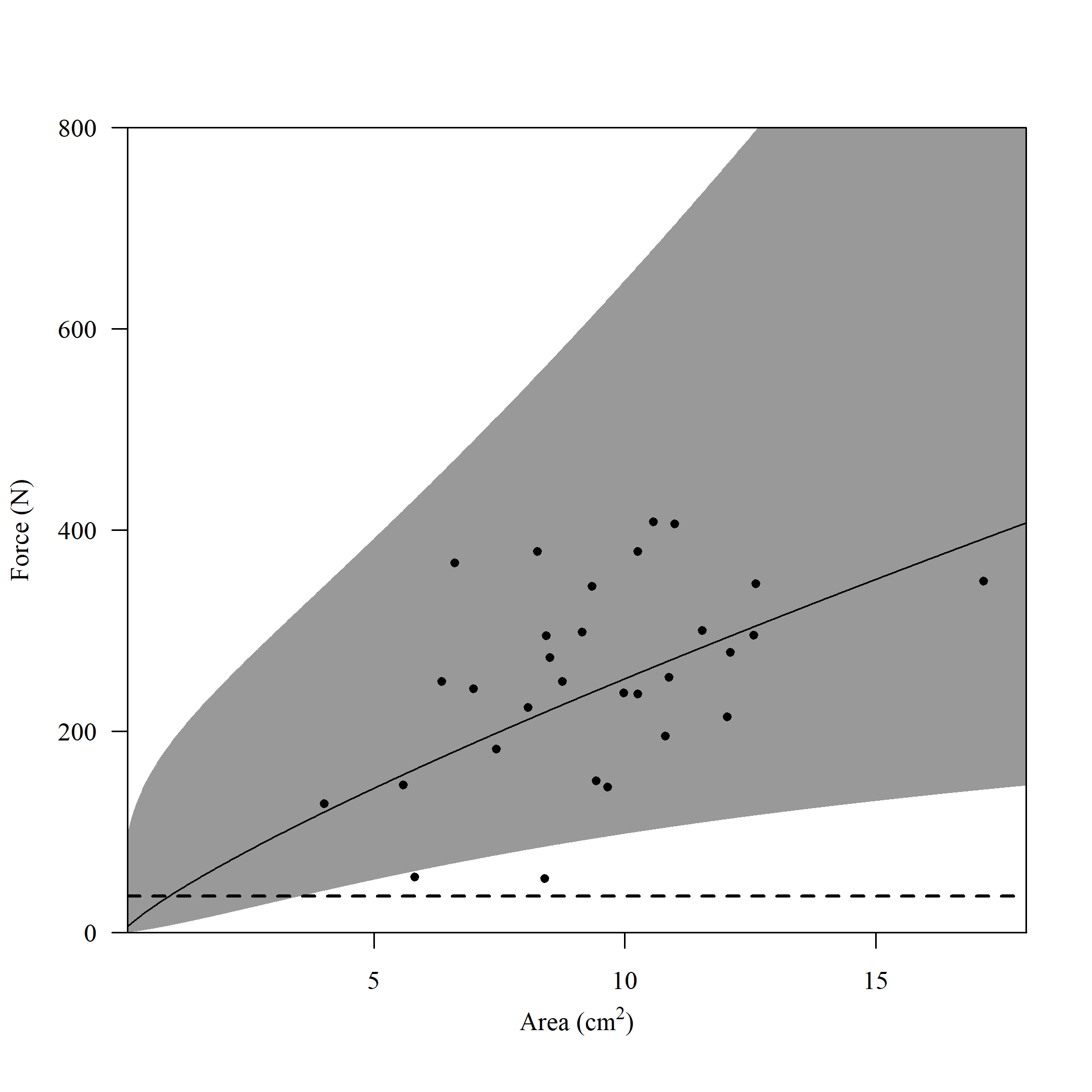
## The following objects are masked from 'package:stats':  
##   
## sd, var



Empirical cumulative density functions for angle (in radians) of pecks vs. pushes in the horizontal plane (top panel) and vertical plane (bottom panel).



Best-fit line of stationary L. gigantea dislodgement force in shear, from data in Denny & Blanchette 2000, J. Exp. Biol.



Forces applied in shear required to dislodge L. gigantea of various aperature areas. Raw data points reproduced from Denny & Blanchette 2000, J. Exp. Biol. The best fit line and 95% prediction interval are shown. The dashed horizontal line represents the largest shear force recorded by the captive oystercatcher in this experiment.

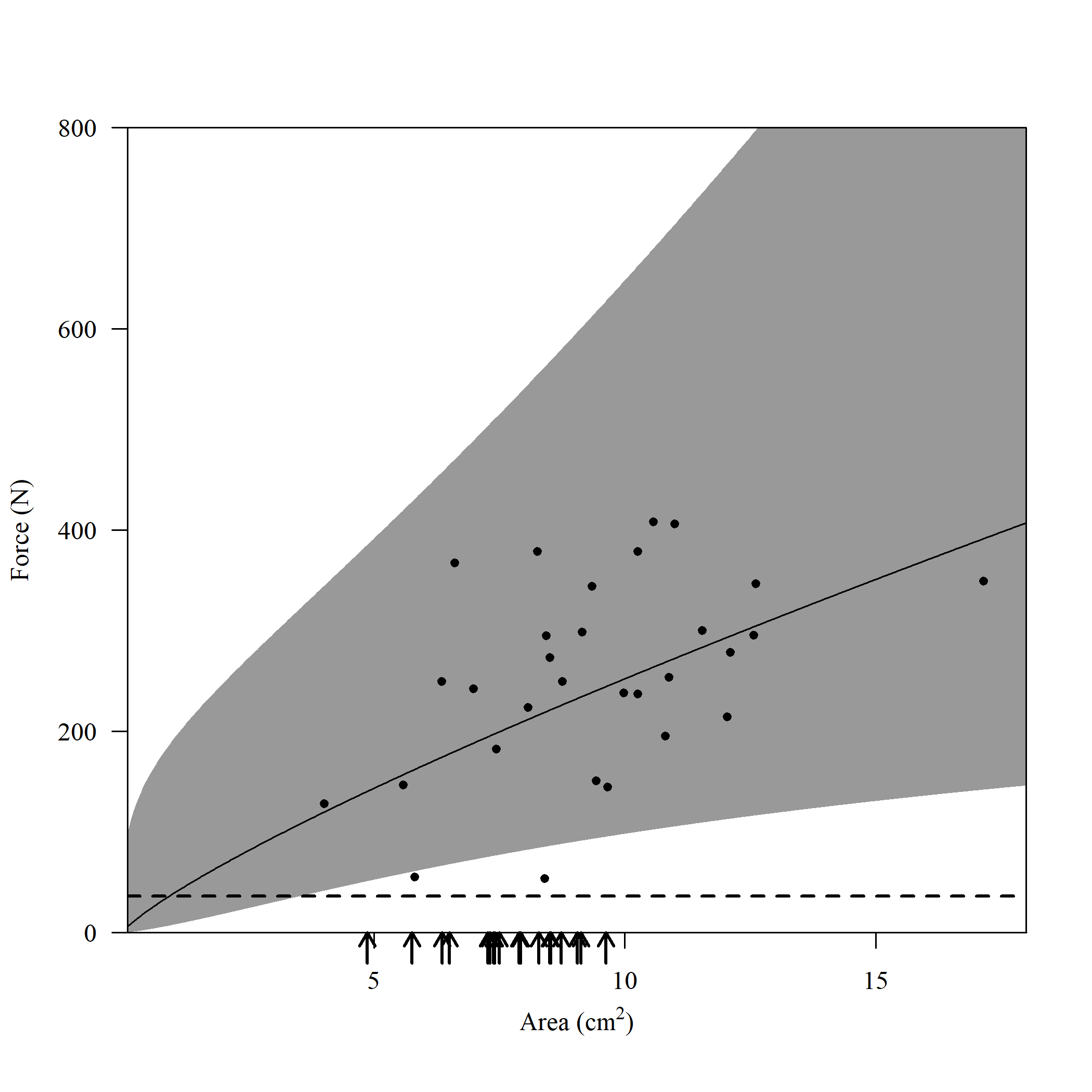
The largest shear force we measured on the limpet force transducer was 36.63 N. Using data from Denny & Blanchette, 2000, *Journal of Experimental Biology*, we fit a power function to their measured dislodgement forces applied in shear to *L. gigantea* that were stationary and had been tapped to produce the highest tenacity. Based on the calculated 95% prediction interval, the largest *L. gigantea* that might be dislodged by a single pecking or pushing force applied in shear (parallel to the substratum) is 3.56 cm^2.

The best fit line through the Denny and Blanchette 2000 data is of the form

Rachel provided aperture area estimates for L. gigantea that were successfully removed by the captive oystercatcher during feeding trials. The limpets had been held overnight in high tide conditions after collection, and then were exposed to a 4 hour “low tide” (or no low tide) prior to being presented to the oystercatcher. Only a subset of the successfully eaten limpets have aperture area data.

Approximate foot aperture area (cm^2) for L. gigantea eaten by the captive oystercatcher. Treatments are Cold Low Tide (CLT), Warm Low Tide (WLT), or No Low Tide (NLT). Aperture area data were missing for 4 CLT limpets and 1 NLT limpet (all shell lengths were recorded).

|  |  |  |
| --- | --- | --- |
| Treatment | Length.cm | Aperture.cm2 |
| CLT | 35.2 | 7.39 |
| CLT | 35.0 | 7.27 |
| CLT | 35.0 | 7.31 |
| CLT | 38.6 | NA |
| CLT | 34.2 | NA |
| CLT | 33.9 | NA |
| CLT | 32.4 | NA |
| WLT | 32.4 | 6.51 |
| WLT | 35.7 | 7.50 |
| WLT | 38.2 | 8.51 |
| WLT | 30.2 | 5.76 |
| WLT | 37.5 | 7.93 |
| WLT | 33.3 | 4.87 |
| WLT | 39.0 | 8.53 |
| WLT | 38.7 | 8.73 |
| WLT | 33.1 | 6.36 |
| NLT | 35.7 | 7.41 |
| NLT | 35.2 | 8.29 |
| NLT | 37.8 | 7.90 |
| NLT | 38.8 | 9.63 |
| NLT | 38.7 | 9.13 |
| NLT | 39.0 | 9.13 |
| NLT | 39.4 | 9.06 |
| NLT | 33.5 | NA |



Forces applied in shear required to dislodge L. gigantea of various aperture areas with a single pull in tension. Raw data points reproduced from Denny & Blanchette 2000, J. Exp. Biol. The best fit line and 95% prediction interval are shown. The dashed horizontal line represents the largest shear force recorded by the captive oystercatcher in this experiment. Arrows on the horizontal axis mark the sizes of L. gigantea successfully dislodged by the captive oystercatcher using multiple strikes.