10th December 2021

Technical Note

Data quality and parameter validity from 1,000 Hz versus 200 Hz sampling frequency on the Curve3 and Force3 Treadmills

Overview

The Curve3 and Force3 treadmills from Woodway are instrumented to provide measurement of horizontal and vertical forces exerted on the treadmill deck as well as high resolution measurement of displacement or distance travelled. The data acquisition hardware is designed and manufactured by Fitness Technology and is a bespoke printed circuit board for these treadmills, model XPV7. The maximum sampling frequency of the XPV7 boards was originally designed at 200 Hz and this served the purpose well over the past decade while the treadmills were being primarily used for testing and training running performance. With a 200 Hz sampling frequency valid and reliable measures of distance, velocity, force and power could be derived.

Given the rich force and displacement data generated by these treadmills greater interest was generated in capability for real-time and asynchronous gait analysis. However, to accurately measure flight and contact times with subsequent calculation of step rate, step length and comparisons between left and right, a time resolution of 5ms (200 Hz sampling) was deemed insufficient for this purpose. Hence the development of the XPV7 hardware and firmware to provide a maximum sampling frequency of 1000 Hz across all channels.

The Pacer Performance System software from Innervations was specifically developed for the Curve3 and Force3 treadmills from their first release and has also been upgraded to maximise the additional capacity provided by the higher sampling rate.

The purpose of this technical paper is to compare data and parameters derived from 200Hz versus 1000Hz sampling frequencies.

Methods

A single 40 second trial was recorded for a subject beginning from a standing start and accelerating to a jog at around 3.3 m/s. Data was collected at 1000 Hz on a Woodway Curve3 using the Pacer Performance System Version 2 – 2021 Release. The treadmill was fitted with a 600 pulse per revolution tachometer for distance measurement. The saved data file was then down sampled to 200 Hz to create a new data file for comparison between the two sample frequencies. Data sets were smoothed using a 4th order Butterworth digital low-pass filter with cutoff frequencies (Fc) listed below. These Fc values were selected to produce similar noise rejection between the two sample frequencies. A range of summary parameters including gait metrics were then calculated using the Pacer software.

Table 1. Filter cut-off frequencies for low pass 4th order digital filter across selected data sets.

Data Set	Data Set	Filter Cut-off (Hz)
Distance	1000	0
	200	0
Velocity	1000	30
	200	20
Acceleration	1000	25
	200	16
Vertical and Horizontal Force	1000	90
	200	60

Summary and Conclusions

The Nyquist criterion requires that the sampling frequency be at least twice the highest frequency contained in the signal or information about the signal will be lost. This is a minimum and higher sampling frequencies will generally produce a more faithful reproduction of the underlying physical signal being measured.

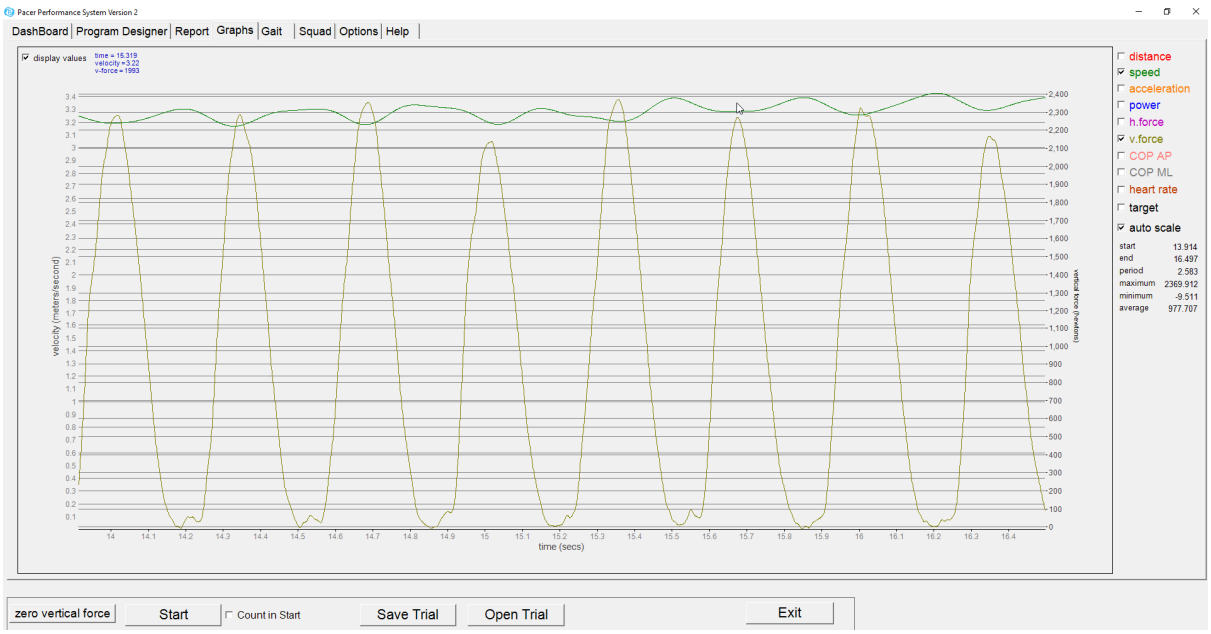
From the analysis completed in this technical note increasing the sampling rate by a factor of five from 200 Hz to 1000 Hz produces much more representative velocity, force, and gait parameters. As can be seen in table 1, filter cut-off's of 50% higher or more could be applied to the 1000 Hz data and still achieve acceptable noise reduction. Much lower filter cut-off's were required to achieve similar signals and measurement parameters for the 200 Hz data. This is a considerable advantage because applying lower cut-off frequencies for the low pass filters increases the attenuation of real physical characteristics within the signal.

For the automatic detection of individual steps during the running gait a threshold of vertical ground reaction force is applied to detect toe off and foot contact. A threshold of 100 N produced acceptable identification of gait events from the 1000 Hz data however a threshold of 235 N was required to eliminate false events when analysing the 200 Hz data. This further demonstrates the advantage of the higher sampling frequency in terms of validity and reliability of gait analysis on the Force3 and Curve3 treadmills.

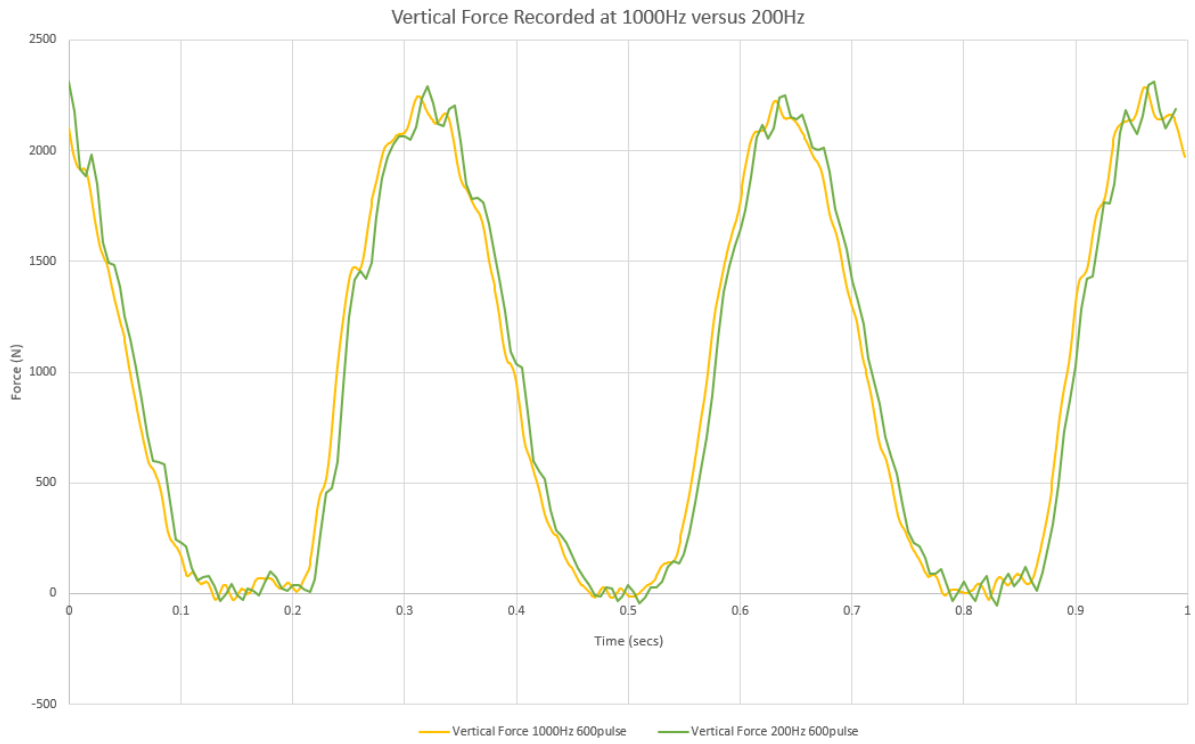
Differences in key gait parameters derived from the 1000 Hz versus 200 Hz datasets were as high as 8.4%. This is due in part to the timing resolution which is 1 ms versus 5 ms comparing the high versus lower sample frequencies.

The improved resolution of kinetic, kinematic and gait parameters provided by the 1000 Hz sampling rate is particularly beneficial for detecting significant but extremely fine differences in left to right symmetry which is a key functionality of the Pacer System.

In conclusion, upgrading the hardware and software of the Woodway instrumented treadmills to 1000 Hz provides much more representative kinetic and kinematic data as well as resulting gait analysis with less strict requirements for data filtering for noise reduction and force thresholding for detection of gait events.

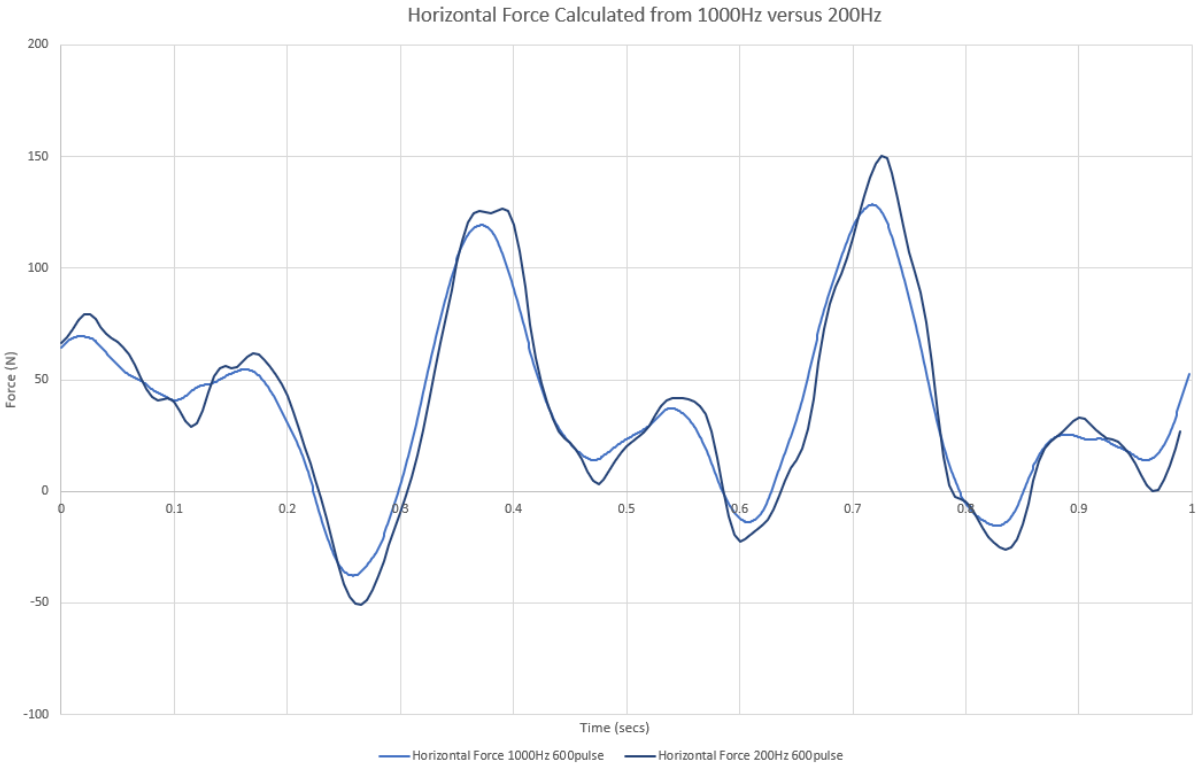


Vertical Force



As can be observed in the figure above of a 1 second example epoch, vertical force sampled at 200 Hz contains more noise artefact and much sharper or quantized perturbations compared to the 1000 Hz data. This is despite the fact that the cutoff frequency for the 1000 Hz data was 50% higher at 90 Hz compared to 60 Hz. This results in different maximum and minimum force values for the 200 Hz data compared to the 1000 Hz sample data. This is an interaction of filter cut-off and sampling frequency and demonstrates that a much higher cut-off frequency can be applied to more optimally filter the 1000 Hz data likely resulting in a more representative signal of the actual forces applied.

Horizontal Force

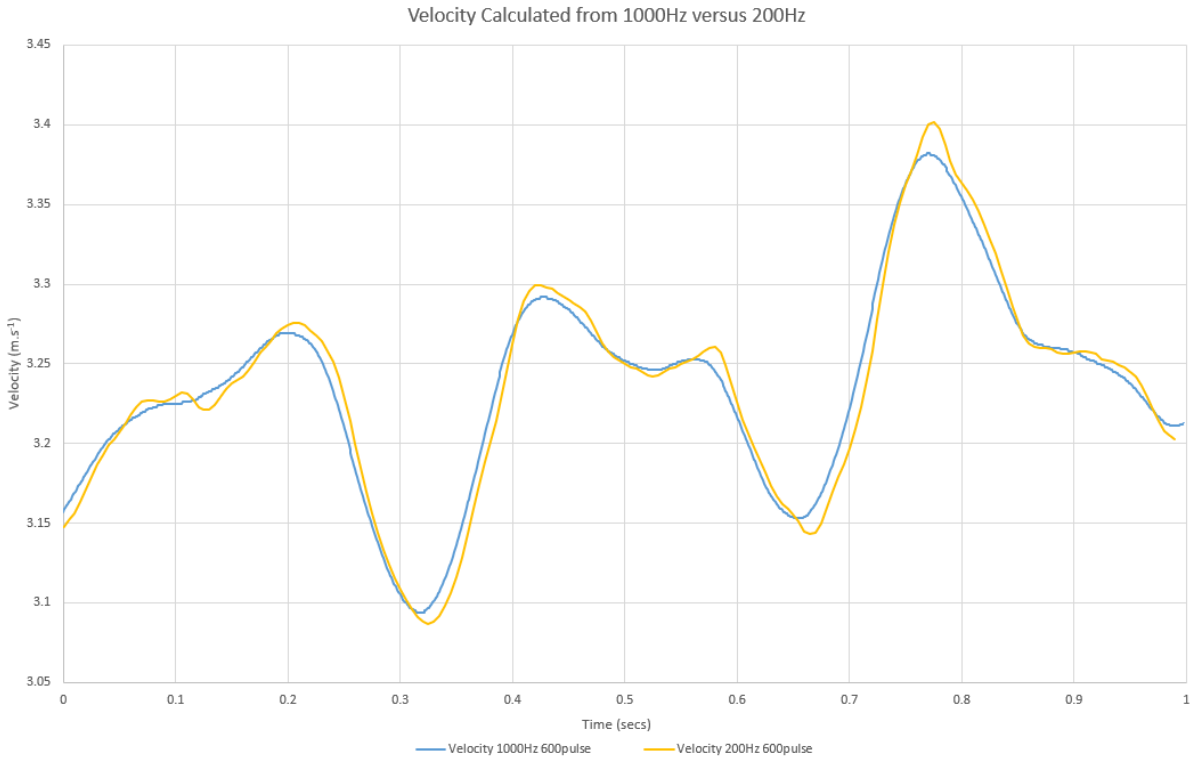


Horizontal force is measured directly in the Force3 using a load cell connected in series to a belt around the subject's waist. For the Curve3, horizontal force is calculated based on acceleration of the treadmill deck and measured parameters of friction and rotational inertia. The result is that horizontal force depends entirely on the accuracy of acceleration data derived through double differentiation of the distance data.

In the figure above it can be observed that there are differences in the magnitude and pattern of horizontal force between the 1000 Hz and 200 Hz derived data. Distance datasets were smoothed at 25 Hz and 16 Hz for 1000 Hz and 200 Hz data respectively prior to double differentiation to produce the acceleration data. Again, there is an interaction between filter cut-off and sampling frequency and a much lower cut-off frequency was applied to the 200 Hz data to produce a representative signal similar to the 1000 Hz data.

Applying lower cut-off frequencies is problematic as there is the risk of attenuating actual real signal while attempting to minimise noise. Therefore, it is likely that the horizontal force calculated from distance data sampled at 1000 Hz is more representative.

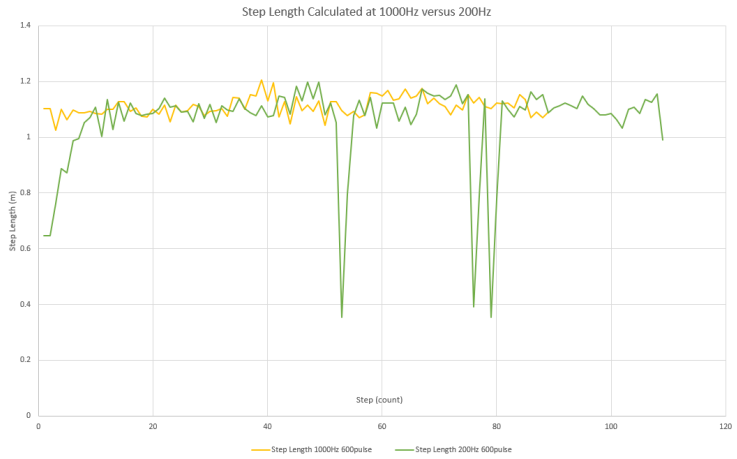
Velocity



Distance data was low-pass filtered at 30 Hz and 20Hz for 1000 Hz and 200 Hz respectively and then differentiated to produce the example 1 second epoch of data above. The two curves are very similar although slightly greater perturbations and minima and maxima are apparent for the 200 Hz data despite the filter cutoff frequency being 50% higher for the 1000 Hz data.

This is an important difference highlighting the superiority of the 1000 Hz sampling rate to provide more representative data requiring less signal processing.

Step Length

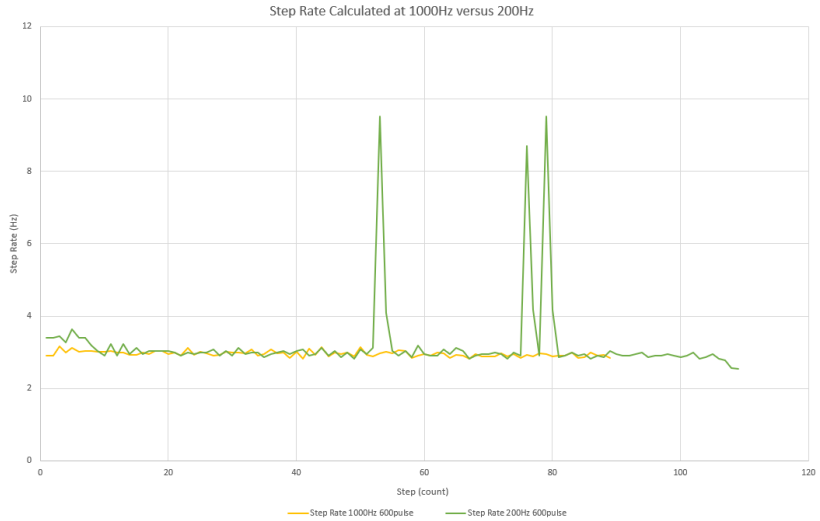


The original models of the Force3 and Curve3 treadmills were designed primarily for testing and training sprint speed, acceleration, and repeat sprint performance. For this purpose, a 200 Hz sampling frequency was perfectly adequate and in fact the early models incorporated a 30 pulse per revolution tachometer which was later upgraded to the current 600 pulse per revolution. The increase in resolution to measure distance was substantial and opened the opportunity to start examining the data produced from the Pacer performance system in more detail.

Exercise and sports scientists, coaches and conditioning specialists became increasingly interested in using these treadmills and the Pacer software to measure parameters of walking and running gait. While early analyses were helpful and some key parameters could be accurately calculated there was a limitation to sampling the various signals from the treadmill at 200 Hz. This is the equivalent of 5 ms between consecutive samples which is borderline for accurate measurement of gait metrics such as foot strike, toe off, step length and step rate.

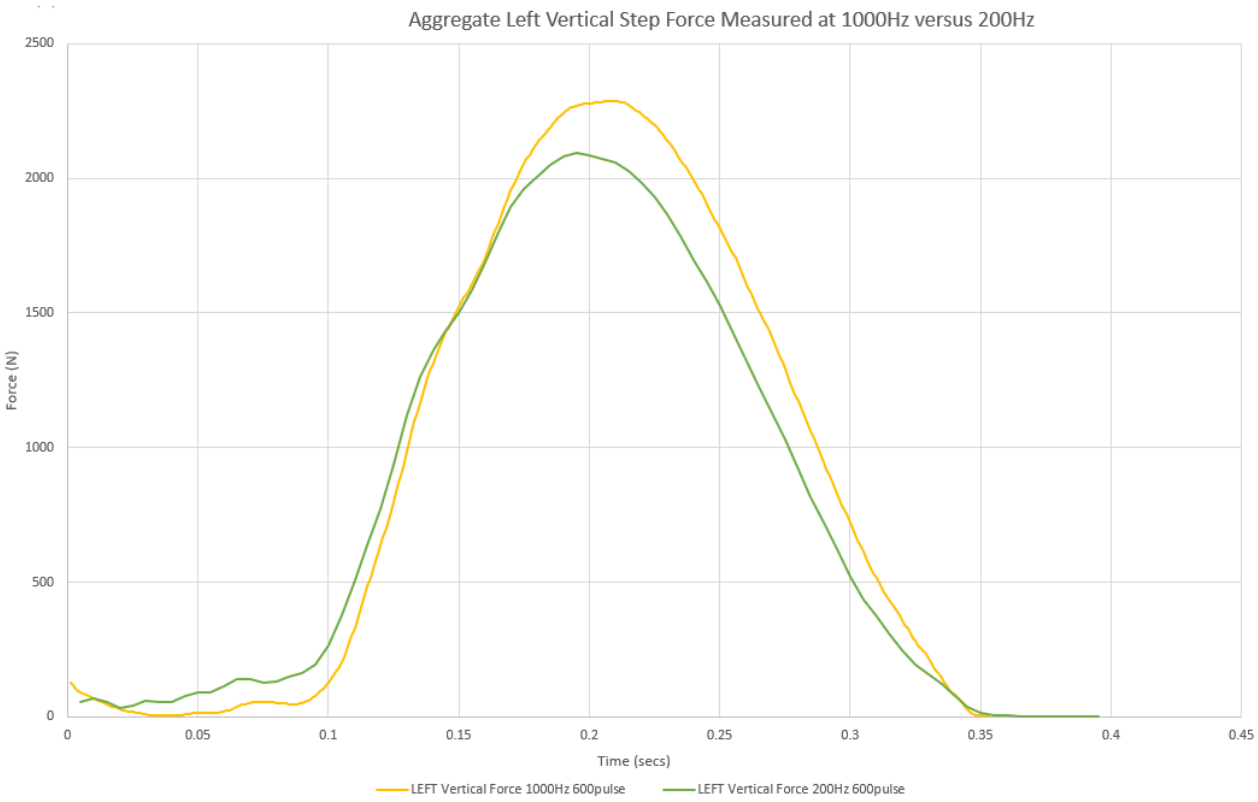
The data acquisition hardware was upgraded and the Pacer software modified to achieve a full 1000 Hz sampling frequency across all force channels and tachometer output. The benefit of this higher sampling rate can be seen in the figure above.

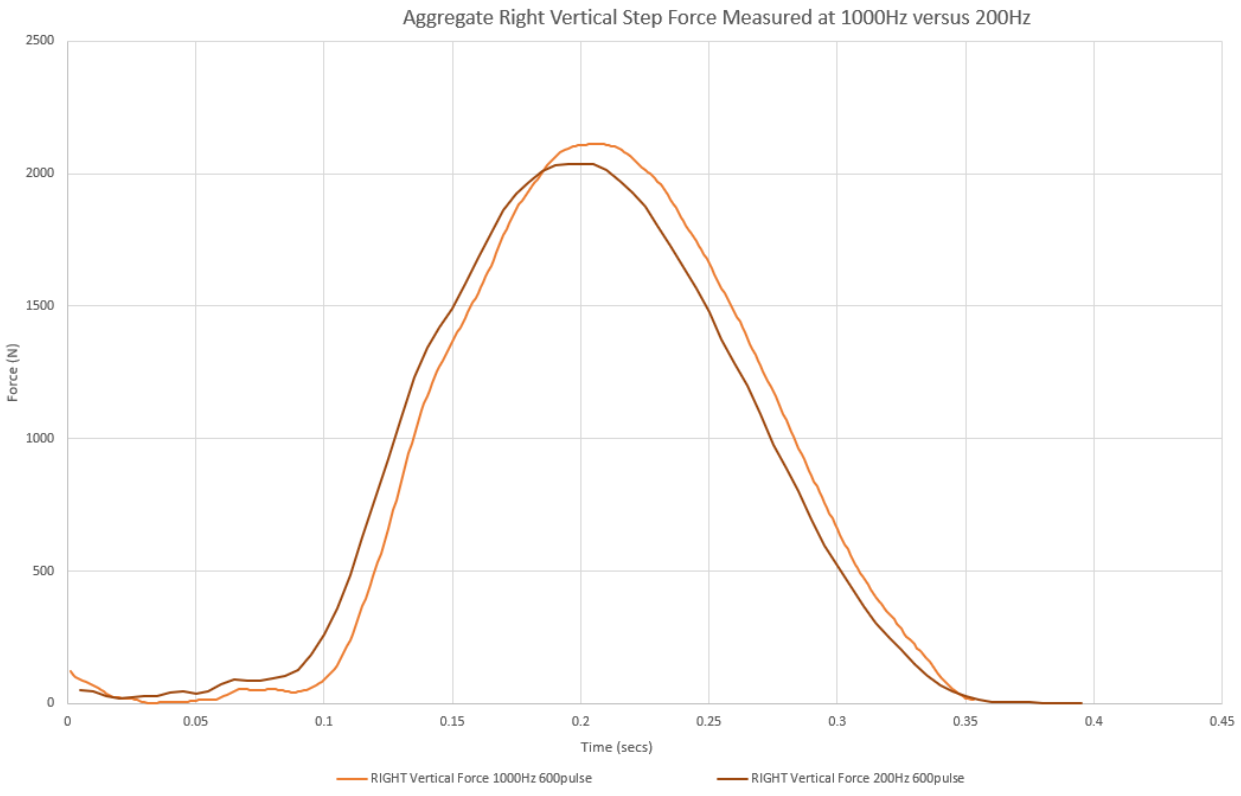
The 200 Hz data results in several false step identifications with resulting errors in measurement of step length. In the example above 89 steps were identified from the 1000 Hz data but 109 steps identified from the 200 Hz data. The erroneous gait analysis can also be observed in the 200 Hz data for identification and measurement of step rate displayed in the figure below.

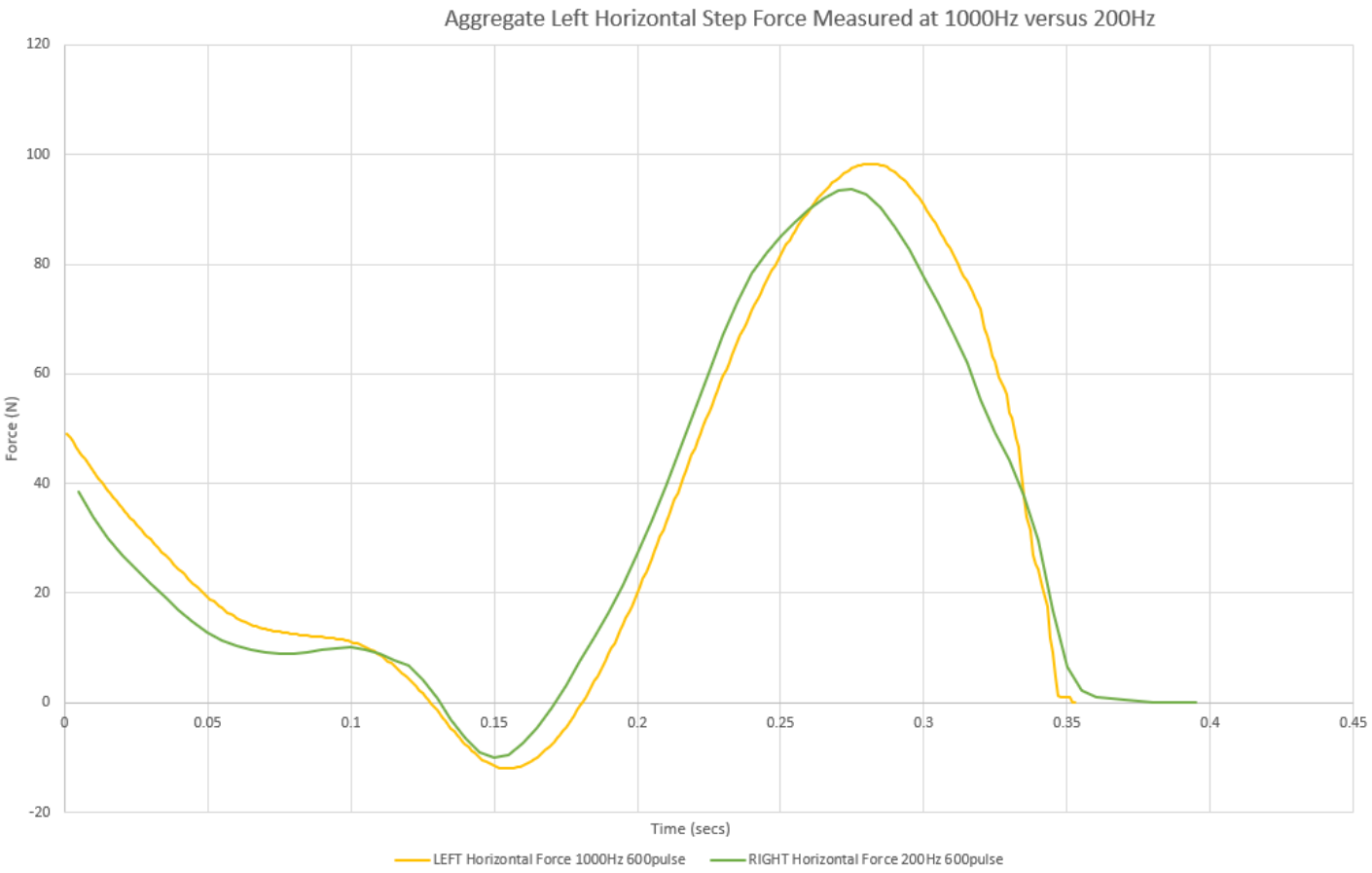


Aggregate Step Force

The following datasets are derived by combining sequential steps into an aggregate or average force by time plot. The left and right steps are averaged separately to provide representative left and right step force time curves across multiple strides. This permits direct comparison of left and right leg force output characteristics across multiple steps. For the 1000 Hz data a filter cutoff of 90 Hz was applied but a much lower 60Hz filter was applied to the 200 Hz data to obtain appropriate smoothing for representative force data.






Aggregate Left Horizontal Step Force Measured at 1000Hz versus 200Hz
120
100
80
60
40
20
0
-20
Force (N)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Time (secs)
LEFT Horizontal Force 1000Hz 600pulse
RIGHT Horizontal Force 200Hz 600pulse

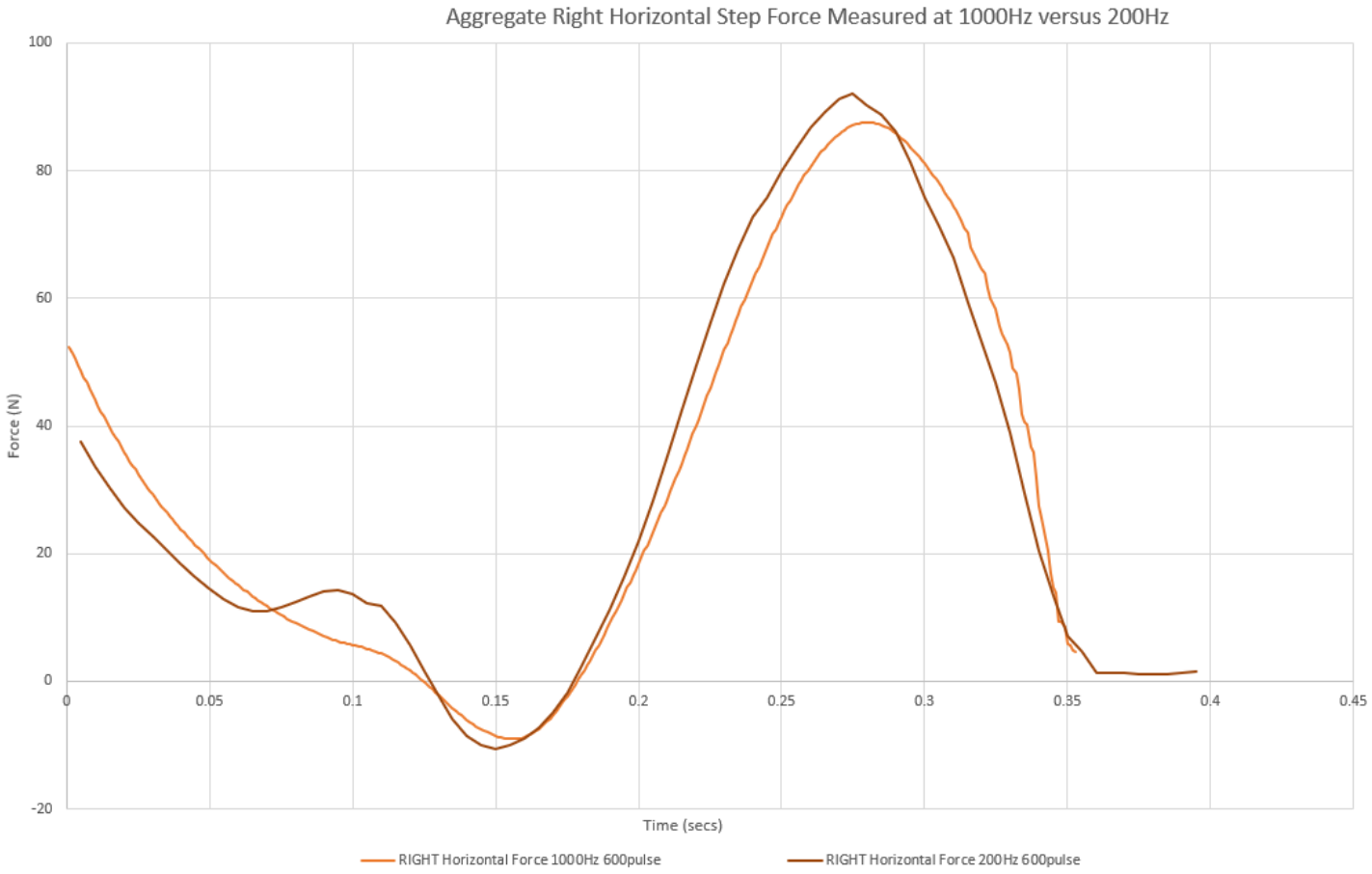

Aggregate Right Horizontal Step Force Measured at 1000Hz versus 200Hz
100
80
60
40
20
0
-20
Force (N)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Time (secs)
RIGHT Horizontal Force 1000Hz 600pulse
RIGHT Horizontal Force 200Hz 600pulse

Table 2. Gait analysis and summary parameters for step rate and length with ratio of left to right. Parameters have been calculated based on 1000 Hz versus 200 Hz sample frequency. Threshold for force to detect flight and contact phases was set to 100N to provide accurate step detection for 1000 Hz data but a 235 N threshold was required to eliminate false step detection for the 200 Hz data.

		Duration	*Total Steps*	*Left*	*Right*	*Average Rate*	*Rate Left*	*Rate Right*	*Ratio*	*Average Length*	*Length Left*	*Length Right*	*Ratio*
A	1000Hz 600pulse 100N threshold	29.998	89	44	45	2.958	2.966	2.95	0.994	1.111	1.107	1.115	0.993
B	200Hz 600pulse 100N threshold	29.998	92	46	46	3.207	3.124	3.291	1.053	1.074	1.084	1.064	1.018
C	200Hz 600pulse 235N threshold	30.01	89	44	45	2.958	2.96	2.956	0.998	1.111	1.11	1.113	0.997
	Difference A-B	0	-3	-2	-1	-0.249	-0.158	-0.341	-0.059	0.037	0.023	0.051	-0.025
	%	0.0%	-3.4%	-4.5%	-2.2%	-8.4%	-5.3%	-11.6%	-5.9%	3.3%	2.1%	4.6%	-2.5%
	Difference A-C	-0.012	0	0	0	0	0.006	-0.006	-0.004	0	-0.003	0.002	-0.004
	%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	-0.2%	-0.4%	0.0%	-0.3%	0.2%	-0.4%

Table 3. Gait analysis and summary parameters for vertical and horizontal force and power with ratio of left to right. Parameters have been calculated based on 1000 Hz versus 200 Hz sample frequency. Threshold for force to detect flight and contact phases was set to 100N to provide accurate step detection for 1000 Hz data but a 235 N threshold was required to eliminate false step detection for the 200 Hz data.

		Average H-Force	*Average H-Force Left*	*Average H-Force Right*	*Average H-Force Ratio*	*Average V-Force Left*	*Average V-Force Left*	*Average V-Force Right*	*Average V-Force Ratio*	Average Power	Average Power Left	Average Power Right	Average Power Ratio
A	1000Hz 600pulse 100N threshold	34.637	33.387	35.886	0.93	933.892	908.261	959.524	0.947	113.806	109.662	117.95	0.93
B	200Hz 600pulse 100N threshold	35.489	35.638	35.34	1.008	928.874	921.03	936.718	0.983	116.609	117.068	116.149	1.008
C	200Hz 600pulse 235N threshold	35.291	33.74	36.842	0.916	936.04	911.668	960.412	0.949	116.003	110.896	121.111	0.916
	Difference A-B	-0.852	-2.251	0.546	-0.078	5.018	-12.769	22.806	-0.036	-2.803	-7.406	1.801	-0.078
	%	-2.5%	-6.7%	1.5%	-8.4%	0.5%	-1.4%	2.4%	-3.8%	-2.5%	-6.8%	1.5%	-8.4%
	Difference A-C	-0.654	-0.353	-0.956	0.014	-2.148	-3.407	-0.888	-0.002	-2.197	-1.234	-3.161	0.014
	%	-1.9%	-1.1%	-2.7%	1.5%	-0.2%	-0.4%	-0.1%	-0.2%	-1.9%	-1.1%	-2.7%	1.5%