THE EFFECT OF STROKE FREQUENCY ON TRANSLATIONAL SPEED AND ACCELERATION IN MANUALLY ACTUATED CASTER BOARDS

Milo Hooper
Massachusetts Institute of Technology
Cambridge, MA, USA

ABSTRACT

Riders of caster boards, like the Razor Ripstik, frequently seek to maximize the performance (i.e. velocity) of their devices. The effect of manual oscillation parameters on caster board response, and therefore performance, is a sparsely studied topic. To illustrate the relation between oscillation frequency and steady-state translational velocity, an experiment utilized three-axis accelerometer data on both panels of a Razor Ripstik Air Pro in conjunction with goniometer data from knee bending in a rider. When cross-correlated with body acceleration profiles, the temporal lag between board actuation and experienced body acceleration was found. It was found that speeds increased with frequency up to 3.7 ± 0.2 Hz at 3.3 ± 1 m/s, and that there is a quadratic, frequency-dependent lag between board actuation and the resulting translational acceleration. Analysis of these relationships would be informative in the development of skills for new caster board riders as well as manufacturers in creating board structures optimized for rapid transit.

INTRODUCTION

Figure 1: A Ripstik Air Pro, one model of caster board [1]

Caster boards are an unorthodox form of two-wheeled manual personal transportation (see Figure 1). Similar to skateboards, they provide ground-plane mobility powered entirely by the activity of the human leg. Their distinguishing characteristic lies in the fact that to actuate the caster board, one must oscillate one's legs in opposite directions perpendicular to the direction of desired motion. The caster board converts this oscillatory motion into translational motion by means of caster wheels mounted to the bottom of the board at an incline sloping down toward the aft end of the board. This results in an unusual pattern of motion for a human being.

Learning to ride a caster board is no easy feat. An experienced rider often has difficulty converting his/her implicit knowledge of which legs to move (and when) in order to successfully operate a caster board into explicit advice for first time caster board riders. The skill is acquired largely through trial and error, yet converges on similar patterns of motion upon skill acquisition. In order to quantify this form of knowledge and inform an entire new generation of caster board riders, it would be useful to understand how the motions one sends to the caster board as a dynamic input affect its steady state acceleration and speed profiles. Of particular interest is the determination of which patterns of leg motion, if any, produce the most effective conversion of oscillatory into translational motion. Such a database of dynamic responses would additionally benefit caster board manufacturers, such as Razor and Street Surfing, in creating optimized board designs for future caster boards.

The frequency of board oscillations is the primary variable in determining the behavior of a caster board. Depth of deflection does affect steady state speed and behavior, but is of lesser consequence to the overall board performance and was held roughly constant for the current experiment. The behavior of a Razor Ripstik Air Pro was examined at different oscillation frequencies using three-axis accelerometer data from the front and aft ends of the board combined with goniometer data to measure knee deflection angle on each leg as well as a single-axis accelerometer placed on the body of the rider.

It is hypothesized that there is likely an optimal frequency of oscillation for any given board, rider, and environment combination that maximizes translational velocity. Intuitively, one expects that a zero-frequency oscillation will produce zero translation; similarly, if one were to oscillate infinitely fast, the board would also not travel anywhere, for it would not have enough time to acquire forward momentum before being depressed in the opposite polarity. Thus one might expect a nonlinear relationship to exist, and with such a relationship, a maximum frequency.

BACKGROUND

A typical caster board is comprised of two flat panels upon which the rider stands, the connecting bar between the panels, and one caster wheel below each panel. The caster wheels are installed in a line symmetric with the connecting bar and pointing towards the front of the board. Caster boards require no contact of the foot with the ground to change or maintain body velocity, even when in a stationary state. The rider's feet never move from their position on the panel tops; instead, the rider's legs are oscillated forward and backward, causing the feet to deflect the panels back and forth perpendicular to the desired direction of translational motion and parallel to the rider's foot orientation. When both board sides are deflected in a regular oscillatory mode 180 degrees out of phase with each other, forward locomotion is achieved.

Mechanically, this locomotion is caused by the tendency of the angled caster wheels to fall back toward their inline configuration after being perturbed to the side, assisted by the board's central torsion bar. The central bar acts as an effective torsional spring, pulling the panels back into alignment. The transient deflective state of the inclined caster holds its panel slightly higher, and the pressure of the rider's weight on the panel helps push it into a lower energy state, forcing the wheel to roll back into inline configuration with some rolling momentum.

Figure 2: (left) The Ripstik model [2] used in this experiment. The front is the on the left side of the image. (right) the angle of a Ripstik Air Pro caster wheel mount is approximately 30 degrees.

Caster boards are fundamentally three-dimensional in their dynamics despite only having two useful degrees of freedom in traversing a planar surface. They are an excellent example of a nonholonomic system: a dynamic system wherein its state is dependent on the path taken to arrive there.

There is little publicly accessible research on the dynamics and behavior of caster boards. Most prior research has focused on their properties in relation to snakeboards (as in Kinugasa et al. 2013 [3]), a hybrid form of personal vehicle that combines the independent caster wheels of caster boards with the purely planar dynamic behavior of a skateboard. Other research (such as in Wada [4] and Ostrowski [5]) has focused on the possibility of utilizing caster board-inspired designs in autonomous robotics applications; while their analyses of feedback control schemes are interesting, their dynamic analysis is largely focused on boards with a fixed, motorized rear wheel and steering entirely directed by the front wheel. Manually actuated caster boards with two wheels, on the other hand, are largely left out of the literature, and the effect of human-driven inputs on caster board performance for human riders has yet to be examined.

EXPERIMENTAL DESIGN

To begin to fill the dearth of human-relevant academic studies of caster board behavior, an experiment was devised to study the effects of manually-controlled oscillation frequencies on steady-state caster board behavior. Frequencies ranging from 0.5 to 4.2 Hz were tested; higher frequencies became physically impractical for the rider to sustain.

APPARATUS AND EXPERIMENTAL ENVIRONMENT

The experimental setup was comprised of a Ripstik Air Pro, two Vernier 3-Axis Accelerometers mounted as shown in Figure 3, and two Vernier Goniometers (GNM-BTA) positioned on the rider's knee joint. For the final set of trial runs, a single-axis accelerometer was mounted on the rider at the waist in order to measure the time lag of acceleration felt on the body from acceleration induced in the board. The three-axis accelerometers were mounted with their x-axes pointing toward the front of the board, y-axes pointing toward the right side of the board as viewed from the back to the front of the top face, and z-axes pointing into the ground, as shown in Figure 3. The accelerometers measured accelerations in terms of meters per second squared, and the goniometers measured angles in terms of degrees. Accelerometers were accurate to within 0.5 meters per second squared, and goniometer resolution was to within 0.12 degrees. Goniometers were calibrated to zero at neutral stance on the Ripstik, with knees slightly bent and feet flat on the panels of the board.

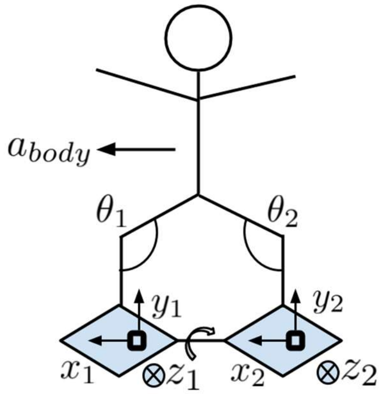

Figure 3: Diagram of accelerometer orientation and placement on Ripstik, as seen from above the Ripstik and facing the rider. Forward velocity was measured in the direction of increasing body acceleration.

In order to facilitate the acquisition of data while minimizing risk to the safety of sensor equipment and the rider wearing the sensors (and holding a laptop while riding), all tests were performed on a carpeted straight hallway to reduce all measured speeds to relatively safe values in case of crash or unexpected ride disturbance. Tests were also performed at hours with minimal hallway activity to avoid collisions with residents.

MEASUREMENT OF ACCELERATIONS AND SPEEDS

Various tests were run with the aforementioned setup at different extreme conditions (fast and slow oscillations) as well as intermediate oscillation frequencies that a rider might consider reasonable for comfortable, non-speed-optimized riding. Slow oscillations are loosely defined as between 0 and 1 Hz, and are usually performed when a rider wishes to have fine control over the caster board's trajectory. Fast oscillations are loosely defined as 3 Hz or higher, and are typically performed only when one seeks to travel significantly faster, at the expense of reduced maneuverability. Frequencies higher than 4 Hz become increasingly uncomfortable to maintain for the rider and result in slower speeds.

Speeds were determined not from accelerometer data, but from measurements of distance between door markers along the hallway divided by the time spent in steady state between doors at a known distance apart. The distance between every pair of doors was calculated from distances relative to the first door (the starting point for most trials), to an estimated accuracy of ± 1.5 meters (5 feet), an acceptable error margin when considering distances of many tens of meters. Timing inaccuracies are estimated at ± 1 second because of Logger Pro delays in stopping data collection and the rider's ability to synchronize termination of data collection with passage of a door marker.

The tests were simple: the rider starts collecting data several meters before the first door marker, accelerates up to steady state by the time the door marker is reached, maintains steady frequency (not difficult for an experienced rider), and stops data collection approximately ten to fifteen seconds later, whenever a convenient door marker passes. The start and stop door markers are encoded into the file for each run, and applicable times for valid data processing are obtained from visual inspection of the data, usually requiring the first few seconds and the last half second of data to be excluded from analysis.

RESULTS AND DISCUSSION

The experiment as described was performed for twenty-seven successful trials to compare frequency with translational speed. Sixteen of those trials additionally contained data on time lags between experienced body acceleration and leg oscillation peaks.

PROCESSING OF RAW DATA

Raw accelerometer and goniometer data for one trial run at 0.75 Hz is demonstrated in Figure 4. Note that goniometer data presented is high-pass filtered (with cutoff frequency of 0.5 Hz) in order to remove any steady state leg offsets from the leg angle of typical stance.

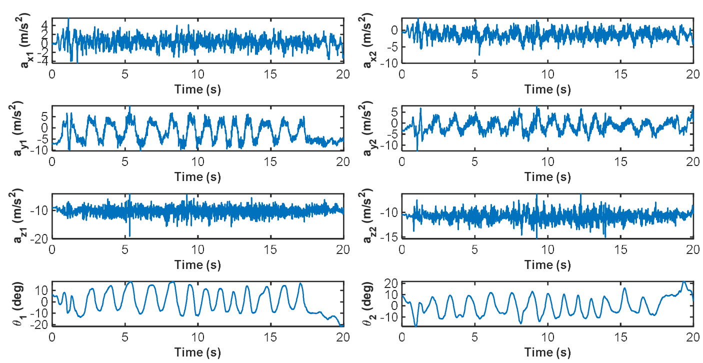

Figure 4: Accelerations in x, y, and z (in order from top) directions for front (left) and aft (right) ends of the Ripstik as well as high-pass filtered goniometer data for a trial run at 0.75 Hz. The first and last few seconds of this run show significant variability in Ripstik behavior due to startup acceleration and deceleration.

Frequency of leg oscillations was determined by a taking a fast Fourier transform (Figure 5) of that signal for each trial, whose peak shows the dominant frequency in the system, corresponding to the overall leg motions and experienced accelerations.

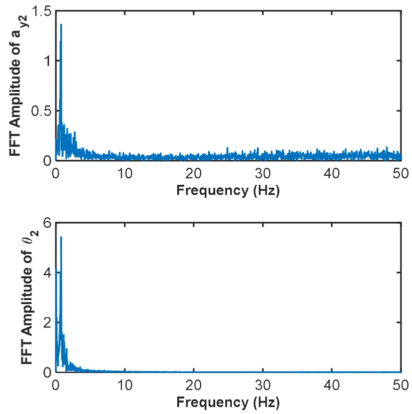

Figure 5: Fast Fourier Transforms of a sample leg-angle and y-axis acceleration profile indicating that, ignoring the effects of noise, a clear overall frequency of oscillation can be determined. This particular data sample was from a 0.75 Hz oscillation.

FINDING THE OPTIMAL OSCILLATION FREQUENCY

A relation between frequency of oscillation and speed of translation consistent with the twenty-seven trial runs' data was produced with MATLAB's Curve Fitting tool as shown in Figure 6, producing a quadratic fit without a constant offset term. Error bars were calculated from estimated frequency errors and a propagation of uncertainty in speed (with speed defined as distance over time).

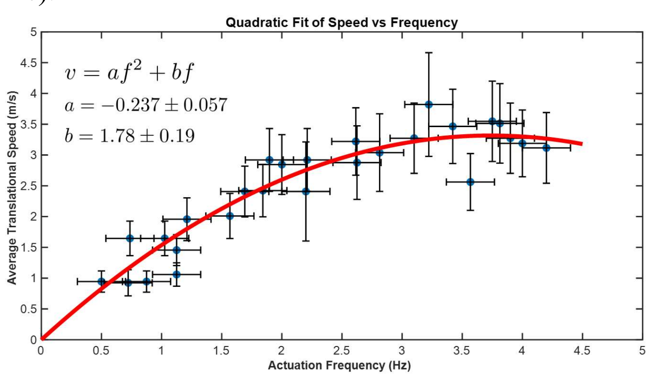

Figure 6: Best-fit quadratic function for translational speed as a function of oscillation frequency. The downtrend after the peak around 3.7 ± 0.2 Hz suggests a convex second-order polynomial is an appropriate fit for the data. When this curve was initially fit with a constant offset term, it was found to be statistically insignificant – not surprising given that zero frequency causes zero motion to occur.

The maximum model speed for the curve (at 95% confidence) is 3.3 ± 1.0 m/s at 3.7 ± 0.2 Hz. The 95% confidence interval encompasses the highest observed translational speeds in the data, which reassures that the fit is likely useful.

There were two particularly strange outliers that are suspected of having been erroneously calculated or, at the very least, are rather uncertain measures: the two data points with the largest residuals from the best-fit curve. If these points were removed and the smaller dataset reevaluated, the precision of curve fit parameters would increase. Even with the outliers, the essentially random distribution of residuals (as shown in Figure 7) indicates that this is an appropriate fit for the data.

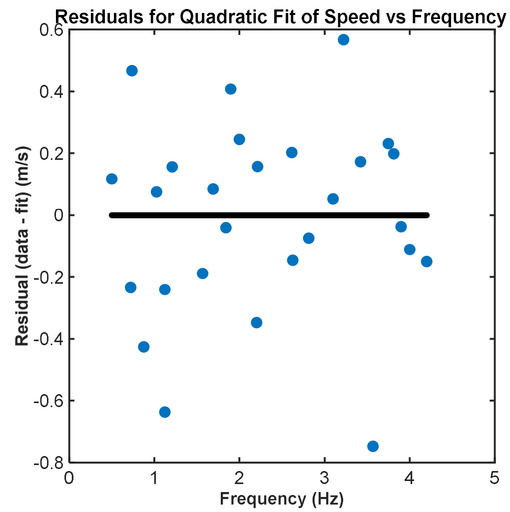

Figure 7: Residuals plotted against y=0. The distribution of residuals throughout the dataset is essentially random, which implies that the quadratic fit is a good function to fit for a relation between driving oscillation frequency and translational speed.

FINDING THE TIME LAG BETWEEN BODY ACCELERATION AND FOOT VELOCITY

Cross-correlations with MATLAB's xcorr function between body accelerometer data and foot velocity data were used to determine their relative time lag. Foot velocity was taken as the derivative of leg angle, and represents how fast the foot is turning into and out of a stroke. An example of a cross correlation done on a medium-speed trial run is shown in Figure 8.

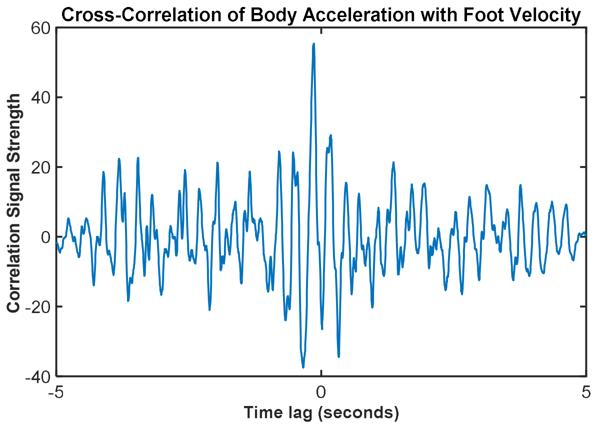

Figure 8: Example of an xcorr result. The graph has been high-pass filtered to remove the dropoff associated with correlating only partial datasets. The highest peak is slightly lagging behind zero seconds, though there is another significant peak immediately after zero seconds.

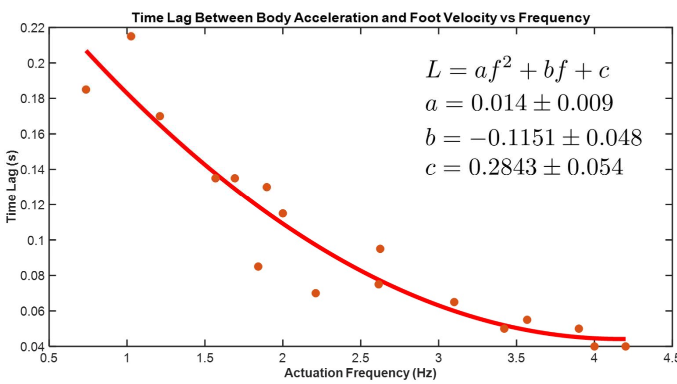

Figure 9: Best-fit quadratic curve for time lag as a function of oscillation frequency. The data trend suggests a nonlinear fit is best, corresponding well to the intuition that a high frequency of motion would leave less time for the body to "catch up" in the period of motion.

The best-fit curve in Figure 9 shows that there is a small time lag (on the order of tenths to hundredths of a second) from the time of maximal foot velocity (corresponding to flat stance, the highest point in foot trajectory on a caster board's plate) and maximal felt acceleration in the direction of translation. There were additionally smaller peaks on the opposite side of zero in the cross-correlation graphs corresponding to slight leads, indicating that there is some accelerating component also occurring immediately before maximal velocity is reached.

Nevertheless, the magnitudes of the time lags certainly decreased as frequency increased, and the data appeared to match well to a quadratic fit as shown by the residuals in Figure 10. It is expected that if one were to test higher frequencies of oscillation, one would observe the trend change asymptotically approach zero.

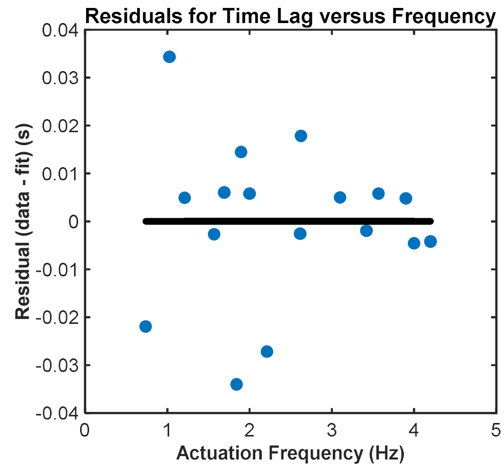

Figure 10: Residuals plotted against y=0. The distribution of residuals throughout the dataset is essentially random, which implies that the quadratic fit is a good function to fit for a relation between driving oscillation frequency and time lag until acceleration is felt.

GENERAL DISCUSSION

There is little relevant literature (as discussed in the Background section) to compare these figures against. However, the larger of the residual values located near the velocity fitted curve maximum in Figure 6 suggest that the theoretical maximum velocity of a caster board should be higher than the current curve claims. Additionally, as the relations between oscillation frequency and speed are significantly influenced by riding surface and rider weight, it is unlikely that such comparisons would be particularly meaningful.

A limitation of this study lies in the large velocity uncertainty that occurs on account of uncertainties in both time and distance measurements; using a proper distance measurement method would have greatly improved the accuracy of this experiment. Additionally, all experiments described here occurred on a carpeted hallway with the same rider on the Ripstik Air Pro; future experiments could examine the effects of different surfaces, rider weights, and caster board models.

CONCLUSIONS

A Ripstik Air Pro on carpeted ground oscillated with roughly similar depths of stroke at different frequencies will produce faster translational velocities as frequency increases, up to a maximum of 3.3 ± 1 meters per second at 3.7 ± 0.2 Hz. After this maximum, performance tapers off. The highest recorded speed from trial data falls within the 95% confidence region for maximum speed in the given conditions. It has been shown that this behavior of the Ripstik can be modeled reasonably accurately by a best-fit quadratic with no constant offset term. This lends credence to the hypothesis that there exists an optimum frequency of oscillation for driving a caster board. Additionally, it has been shown that the time lag between body acceleration in the direction of translation and maximal foot velocity decreases quadratically with rising oscillation frequency. Future work in this domain could involve studies of the depth of stroke as well as the effect that different surfaces have on performance maxima (in the transient and steady state domains). Those who seek to maximize the performance of their caster boards would benefit from such work as they would from the current study, which informs a target range of frequencies of leg oscillation to maximize translational steady-state velocity.

ACKNOWLEDGMENTS

The author would like to thank Prof. Rohit Karnik and Dr. Barbara Hughey for their assistance in this project, as well as the residents of East Campus Second West for tolerating many hours of furious Ripstik riding up and down the hallway at night this semester.

REFERENCES

[1] Discounto (2019) Ripstik Air Pro [image] Available at: http://src.discounto.de/pics/Angebote/2011-04/117057/140552_RAZOR-Ripstik-Air-Pro_xxl.jpg

[2] Bargainmax UK (2019). Ripstik Air Pro Caster Board. [image] Available at: https://www.bargainmax.co.uk/media/catalog/product/r/i/ripstick-air-caster-board-black.jpg.

[3] Kinugasa, K., Ishikawa, M., Sugimoto, Y., and Osuka, K., 2013, “Modeling and Control of Casterboard Robot,” Proceedings of the IFAC Symposium on Nonlinear Control Systems, Toulouse, France, September 4-6, 2013, pp. 785-790

[4] Wada, M., Tominaga, Y., and Mori, S., 1995, “Omnidirectional Holonomic Mobile Robot Using Nonholonomic Wheels,” Proceedings of the IEEE International Conference on Intelligent Robots and Systems, Pittsburgh, PA, August 5-9, 1995, pp. 446-453

[5] Ostrowski, J., Desai, J., and Kumar, V., 2000, “Optimal Gait Selection for Nonholonomic Locomotion Systems,” International Journal of Robotics Research, Vol. 19, Issue 3, pp. 225