The Biomechanics and Energetics of Skateboarding

Bryant Pham

University of Colorado at Boulder, phambt@colorado.edu

Follow this and additional works at: https://scholar.colorado.edu/iphy_gradetds

Part of the Exercise Physiology Commons

Recommended Citation

Pham, Bryant, "The Biomechanics and Energetics of Skateboarding" (2016). Integrative Physiology Graduate Theses & Dissertations. 46.
https://scholar.colorado.edu/iphy_gradetds/46

This Thesis is brought to you for free and open access by Integrative Physiology at CU Scholar. It has been accepted for inclusion in Integrative Physiology Graduate Theses & Dissertations by an authorized administrator of CU Scholar. For more information, please contact cuscholaradmin@colorado.edu.
THE BIOMECHANICS AND ENERGETICS OF SKATEBOARDING

by

BRYANT THANH PHAM

B.A., UNIVERSITY OF COLORADO, BOULDER, 2013

A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado in partial fulfillment
of the requirement for the degree of
Master of Science
Department of Integrative Physiology

2016
This thesis entitled:

The Biomechanics and Energetics of Skateboarding

written by Bryant Thanh Pham

has been approved for the Department of integrative Physiology

______________________________
Rodger Kram, Ph.D.

______________________________
Alena Grabowski, Ph.D.

______________________________
William Byrnes, Ph.D.

Date________________________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

IRB protocol # 13-0161
Abstract

Pham, Bryant (MS, Integrative Physiology)
The Biomechanics and Energetics of Skateboarding
Thesis directed by Professor Rodger Kram

I investigated the ground reaction forces (GRF), stride kinematics and metabolic cost of skateboarding on an instrumented treadmill. Superficially, skateboarding appears to be a hybrid of walking, running, and cross-country skiing. I hypothesized that the push-foot in skateboarding would exhibit a vertical GRF peak similar in shape to running but with a lower magnitude. Further I hypothesized that the push-foot would exhibit greater propulsive GRF than braking GRF. Regarding stride kinematics, I hypothesized that skateboarders would increase their stride length (sL) at faster speeds. Finally, I hypothesized that skateboarding would have a smaller metabolic cost compared to walking and running at comparable speeds. Subjects (9 males/2 females) skateboarded on a force-instrumented treadmill at 1.00, 1.25, 1.50, 2.00, 2.50, 3.00, 3.50, and 4.00 m*sec\(^{-1}\), walked at 1.25 m*sec\(^{-1}\), and ran at 3.0 m*sec\(^{-1}\). Upon GRF analysis, I discovered two distinctly different groups of skateboarders: subjects who demonstrated a braking force (“brakers”) and subjects that did not (“non-brakers”). The peak vertical and horizontal GRF for brakers resembled running with half of the magnitude. Both groups showed decreased SF at faster speeds, but brakers used slower SF than non-brakers. Walking and skateboarding 1.25 m*sec\(^{-1}\) had the same metabolic cost at but at 3.0 m*sec\(^{-1}\), skateboarding required approximately half the metabolic cost of running. Skateboarding is a unique mode of locomotion, with two distinctly different forms, that allows a person to move at a running velocity with the GRF and metabolic cost of walking.
## CONTENTS

**CHAPTERS**

I. INTRODUCTION ........................................................................................................... 5
II. METHODS ....................................................................................................................... 8
III. RESULTS ..................................................................................................................... 11
IV. DISCUSSION ............................................................................................................... 18
V. BIBLIOGRAPHY .......................................................................................................... 26
TABLES

1. Average ground reaction forces, impulses, and stride kinematics in relation to velocity............ 13

2. Sample subject data for braking, braking and rolling resistance impulse per stride.................. 14
Figures

1. Sample vertical and horizontal ground reaction force traces for push-foot and board-foot....... 11

2. Ground reaction force traces in relation to velocity

   2a. Braker subject data ................................................................. 12

   2b. Non-braker subject data ......................................................... 12

3. Stride Kinematics

   3a. Stride frequency in relation to velocity for brakers and non-brakers.......................... 16

   3b. Stride lengths in relation to velocity for brakers and non-brakers........................... 16

4. Metabolic data comparing skateboarding to walking and running..................................... 17

5. Example ground reaction forces for walking and running................................................. 18

6. Linear extrapolation with existing metabolic data ......................................................... 23

7. Different wheel mounting categories found in skateboarding.......................................... 25
Chapter 1: Introduction

Our human ancestors began walking and running bipedally ~4 million years ago (Crompton et al., 2011) and the biomechanics and energetics of walking and running have been extensively studied (Alexander, 2003). The “laufmaschine”, invented in 1817, combined bipedal gait with foot-ground contact and two wheels (Minetti et al., 2001). Laufmaschine enhances the speed and reduced the energetic cost of human powered locomotion but were soon surpassed by rotary crank bicycles (Minetti et al., 2001). There have also been many scientific studies of bicycle biomechanics and energetics (Wilson, 2004).

In the 1950s skateboarding emerged as an alternative mode of transportation that combines unilateral legged propulsion with small diameter wheels. Superficially, skateboarding appears to be a hybrid between bipedal gait and laufmachines; there is one leg used for propulsion with significant periods of coasting while rolling on wheels. Today, over 11 million people worldwide skateboard and the industry generates an estimated $4.8 billion in annual retail sales (Montgomery T., 2009). Yet to date, only one scientific paper has quantified the energetics and kinematics of skateboarding as a form of transportation (Board and Browning, 2014). That study had subjects skateboard overground over a certain distance while measuring velocity, stride kinematics and metabolic costs of three self selected speeds: slow, typical, and fast (Board and Browning, 2014). As a biomechanist, the lack of research and my personal passion for skateboarding motivated me to further investigate the ground reaction forces of skateboarding, how the energetics of skateboarding compare to other forms of locomotion, and how the biomechanics and energetics are connected.

Prior to conducting my research, I tried to predict the biomechanics of skateboarding from my knowledge and observations of the movements and forces involved in walking, running, bicycling and cross-country skiing. Walking is often described as an inverted pendulum system during the single
support, stance phase. In walking the whole-body center of mass (COM) reaches its highest vertical position during the midstance of the weight bearing leg resulting in gravitational potential and kinetic energy being out-of-phase with one another (Farley and Ferris, 1998). The average peak, vertical GRF in walking is ~1.3 body weights (BW) (Farley and Ferris, 1998). In skateboarding, one leg remains on the board while the other legs swings forward, is placed on the ground and pushes backwards. Thus, a stride cycle in skateboarding can be defined as the time from when the push-foot makes contact with the ground until it makes contact with the ground again. Prior to placing the push-foot down, it appears that the COM is at its highest point and, the gravitational potential energy is at its maximum while the horizontal velocity and kinetic energy are at their minima. In running the COM is at its lowest point at the middle of the stance phase of the weight-bearing leg. During the first half of the stance phase, the knee flexes and during the second half of the stance phase the knee extends. The peak vertical GRF during running is approximately 2.5 BW (Munro et al., 1987). In skateboarding, the leg that pushes on the ground appears to follow a similar knee flexion/extension pattern. In bicycling, there is no vertical work done on the COM, the saddle reduces the forces needed at the legs to support body weight, and the wheels minimize the energy lost to collisions. In skateboarding, the wheels are considerably smaller, with greater rolling resistance than a bicycle and the legs must support body weight throughout the gait cycle. In classic cross-country skiing (XC), the leg motions resemble walking and running, the legs must support body weight and there are almost no braking forces (Kehler et al., 2014). The XC skier generates propulsive forces with their poles and by alternately kicking backwards with their legs/skis. Cross-country skiing and skateboarding are similar in that both are forms of pulsatile propulsion in which the person repeatedly pushes and then glides/coasts. Thus overall, skateboarding seems to combine selected aspects of walking, running, bicycling, and cross-country skiing.
In this study, I investigated how the biomechanics and energetics of skateboarding change across speed and compared my results to walking and running at matched speeds to compare between the different forms of locomotion. I tested five hypotheses. Based on my intuition and the similarity of the knee flexion/extension patterns in running and skateboarding, my first force hypothesis (F1) was that the vertical ground reaction forces in skateboarding would be similar in pattern to running but lower in magnitude. Based on the forces in cross-country skiing (Kehler et al., 2014), I hypothesized (F2) that the horizontal anterior-posterior GRF in skateboarding would exhibit only a brief, small magnitude braking force and an extended, larger magnitude propulsive force. Based on the seminal study of Board and Browning (2014), my first kinematic hypothesis (K1) was that at faster speeds, skateboarding would require longer strides. I also hypothesized (K2) that at a given speed, stride lengths would be longer in skateboarding that during either walking or running. Finally, based on previous studies of walking, running, XC skiing (Kehler et al. 2014), and bicycling (Minetti et al., 2001), I hypothesized that skateboarding would require less metabolic energy than walking or running at comparable speeds primarily due to the rolling wheels (E1). To test these hypotheses, I investigated the biomechanics of skateboarding using a force-measuring treadmill (FTM) and measured the metabolic cost of skateboarding using expired gas analysis.
Chapter 2: Methods

I collected data on 11 healthy volunteers [9 males / 2 females; mass 74.35kg±11.83, height 1.75m±8.02, age 20.8±2 years old (mean±SD)]. Recruited subjects had a minimum of one year of skateboarding experience prior to participating. All of these healthy subjects gave written, informed consent according to the University of Colorado Institutional Review Board approved protocol (13-0161). I use the term “board-foot” for the foot that remains on the skateboard for body weight support, and “push-foot” for the foot that provides propulsion by pushing on the treadmill belt or ground. Six of the participants preferred the “Regular” configuration with their left foot as the board-foot while five participants preferred to use their right foot as the board-foot. This latter configuration is termed “Goofy”.

Subjects walked (1.25m*s⁻¹), ran (3.0m*s⁻¹), and skateboarded (1.0, 1.25, 2.0, 2.5, 3.0, 3.5, 4.0m*s⁻¹) on a custom-built, dual-belt treadmill with an AMTI force platform (model ZBP-7124-6-4000) mounted underneath one treadmill (AMTI, Watertown, MA). The treadmill consisted of two belts side-by-side, each measuring 51cm wide and 191 cm in length. Each subject used their own familiar skateboard configuration to minimize discomfort or unfamiliarity with a different board they were not accustom to, but I installed a standard set of wheels (76mm diameter, 59mm width/contact patch, 76a durometer). These wheels provided mediolateral friction on the treadmill belts to prevent any slipping or drifting. I instructed the subjects to try and maintain a constant position on the treadmill during data collection. For safety, each subject wore a waist belt secured to the ceiling with a slack rope. All subjects adapted quickly (<5min) to skateboarding on the treadmill.

In the first session, I collected subjects’ GRF data over a range of skateboarding speeds and calculated stride frequency from those data. From each one-minute trial, I recorded GRF data (at 1000
Hz sampling frequency) during the last 15 sec at 1.0, 1.25, 2.0, 2.5, 3.0, 3.5. and 4.0 m*s⁻¹. Because only one treadmill was force instrumented, subjects first skated in one direction with the push-foot on the instrumented treadmill while their board-foot and skateboard were on the other treadmill. After completing all the speeds, the subject skateboarded again but in the opposite direction with the belts running in reverse to capture force data for the board-foot. I did not record the GRF of walking or running because there are many reference values in the literature.

In the second session, I collected rates of oxygen consumption and carbon dioxide production for 5 min trials of standing in place, skateboarding, walking at 1.25 m*s⁻¹, and running at 3 m*s⁻¹ and averaged the last 2 minutes for expired gas analysis. I collected and analyzed each subject’s expired air using indirect calorimetry (Parvo Medics, Sandy, UT). I report metabolic data as the rate of oxygen consumption to ease the comparison with other studies in the literature. However, in order to calculate cost of transport, I used the conversion factor of 20.1 Joules per mL of O₂ (Taylor et al., 1982).

I wrote custom scripts in MATLAB (Natick, MA, USA) to calculate the forces, impulses, and stride kinematics of each subject. After data collection, I filtered each subject’s GRFs using a fourth-order Butterworth low-pass filter, with cutoff frequencies that ranged between 15 and 25Hz. From the filtered force recordings of every stride (from the contact of the push-foot with the treadmill until the next time it made contact with the treadmill again) for each velocity for every subject, I determined: the push-foot contact time, when the anterior-posterior forces crossed zero, and the toe-off time of the push-foot. I identified the instance of foot-treadmill contact by visual inspection of the GRF-time traces and averaged the peak braking and propulsive forces for each trial and then averaged across subjects. To calculate the braking and propulsive impulses, I used MATLAB to integrate the horizontal GRF over time.
To take rolling resistance into account, I determined the coefficient of rolling resistance ($C_{RR}$) by measuring the force with a tension scale required to tow a subject of known weight standing on a skateboard while the treadmill was rolling at 4.00m/s. I calculated $C_{RR}$ as the average towing force divided by the combined weight of the skateboard and skateboarder. I determined that $C_{RR}$ was 0.010.

I used linear regression analysis to compare GRF and stride frequency data for brakers and non-brakers (separately) across the range of velocities. For the metabolic data I used independent t-tests to compare between brakers and non-brakers at both speeds. I also used dependent t-tests in order to compare skateboarding, walking, and running.
Chapter 3: Results

I initially planned to analyze my data for all subjects as one group. However, upon initial visual inspection, I discovered two distinctly different ground reaction force (GRF) patterns. Approximately half the subjects (6 of 11) demonstrated a period of anterio-posterior braking GRF with the push-foot during nearly every push phase (Figures 1 and 2a). Subsequently, I refer to that group as “brakers”. Conversely, the other five subjects, the “non-brakers”, were far less consistent, and exhibited no braking forces during more than 50% of their strides (Figure 2b). There were no obvious differences between brakers and non-brakers in terms of skateboarding experience.

Figure 1: Vertical and horizontal ground reaction force (GRF) in units of body weight (BW) for a braker skateboarding at 4m/s. Subjects shift their weight off of the board-foot to the push-foot at the beginning of a push. Note that the maximum board-foot vertical ground reaction force was ~1BW. The peak vertical GRF of the push-foot consistently exceeded 1BW in all brakers at speeds of 2.0m*sec^-1 and greater. The horizontal GRF trace shows a clear braking and propulsive pattern.
Figure 2a: Averaged vertical and horizontal GRF for brakers (n=6). The vertical forces resemble the half sinusoidal waves found in running. Peak vertical GRF increased with velocity ($p<0.05$). The horizontal forces show a sinusoidal pattern with braking force followed by a propulsive force.

Figure 2b: Averaged vertical GRF ($p<0.05$) and horizontal GRF ($p<0.05$) for non-brakers (n=5) increased at faster velocities. Note the absence of braking forces and that the vertical peak GRF magnitudes were much smaller than for non-brakers and did not change with speed.
In the braker group, anterio-posterior force recordings of the push-foot showed a sinusoidal pattern of braking followed by propulsion. The peak magnitudes of the braking and propelling forces both increased at faster speeds (p<0.05) (Figures 1 and 2a; Table 1). The peak propulsive force magnitudes were consistently greater than the peak braking forces (p<0.05) (Figure 2a, Table 1). Across velocity, the propulsive impulse per stride (force integrated over time) was consistently greater than the braking impulse (p<0.05) (Table 1) but the propulsive impulse per stride did not change significantly (p=0.312).

The patterns of the vertical GRF traces of the push-foot for the braker group resembled half-sine waves (Figure 1, 2a). In the present study, at 3.0 m*sec$^{-1}$, brakers exhibited an average peak vertical GRF of 1.3 BW (Table 1) while non-brakers averaged just 0.6 BW (Table 1). Both brakers and non-brakers had greater peak vertical GRFs at faster speeds. For brakers, the regression equation was: Peak vertical GRF = 0.221v + 0.673, where GRF is in BW and v is in m*sec$^{-1}$ (p=1.48e$^{-7}$). For non-brakers, the regression was: GRF = 0.182v + 0.243 (p=0.02). The brakers exhibited greater peak magnitudes of vertical ground reaction force than the non-brakers at all tested speeds. The peak vertical GRF of the brakers were consistently higher by at least 50% compared to non-brakers.

**Table 1:** Table of averaged GRF and stride kinematic values with standard deviations for brakers(n=6) and non-brakers(n=5).
Compared to the brakers, the non-brakers exerted smaller and less consistent forces (Figure 2b, Table 1) for shorter durations. Most strides lacked any braking force and the propulsive force traces resembled half-sine waves (Figure 2b). The peak magnitudes of the propulsive forces were approximately half those of the braker group. Non-brakers did not increase their propulsive impulse per stride at faster velocities (p=.605). Further, vertical force peaks were greater at faster speeds (Figure 2b, Table 1) (p<0.05). The patterns of the vertical GRF traces of the push-foot for the non-braker group also resembled half-sine waves (Figures 1, 2b). The peak vertical GRF never exceeded 1.0BW (Table 1).

There were also differences between the brakers and non-brakers in terms of stride kinematics. Both brakers (p=0.0034) and non-brakers (p=0.0034) used slower stride frequencies at faster speeds. However, the non-brakers utilized consistently faster stride frequencies and shorter strides compared to brakers consistent with their smaller propulsive forces and impulses per stride (Figures 3a and 3b).
Figure 3:

a. Average (±standard error) stride frequencies for brakers and non-brakers. Both groups showed a decrease in stride frequency at faster speeds. The non-brakers used greater stride frequencies than brakers. The rate of change was similar between the two groups as velocity increases.

b. Average (±standard error) stride lengths for brakers and non-brakers. Both groups showed an increase in stride length at faster speeds. The brakers demonstrated greater intersubject variance than the non-brakers. However the brakers took longer strides and at faster speeds they increased their stride length more than non-brakers at all velocities.
Skateboarding (13.31 ± 1.40 mL O₂kg⁻¹min⁻¹) and walking (12.81 ± 0.67 mL O₂kg⁻¹min⁻¹) incurred similar rates of gross oxygen consumption at 1.25 m*sec⁻¹ (p=0.30), however at 3.0 m*sec⁻¹, skateboarding (20.36 ± 2.54 mL O₂kg⁻¹min⁻¹) required approximately half the energy compared to running (37.77 ± 0.91 mL O₂kg⁻¹min⁻¹) (Figure 4) (p<0.05). Despite the biomechanical differences, at both the walking (p=0.15) and running (p=0.10) speeds, the energetic cost of skateboarding were not significantly different between the brakers and non-brakers.

**Figure 4:** Rates and standard deviations of gross oxygen consumption for walking, running, and skateboarding at matched velocities. In both walking (p=0.15) and running (p=0.10), there was no significant difference between brakers and non-brakers. Combining both groups (brakers and non-brakers) there was no statistical difference between walking and skateboarding (p=0.30). But at 3.0m*sec⁻¹ skateboarding required about half the oxygen consumption as running.
Chapter 4: Discussion

I accept hypothesis F1; the vertical GRF patterns of the push-foot were similar to running but lower in magnitude (brakers=1.324BW, non-brakers=0.597BW vs. running=2.51BW (Munro et al.,1987)). The overall shape of the vertical GRF of the pushfoot in skateboarding resembled a half sine wave with a peak occurring approximately midway between contact and toe-off.

![Graph showing vertical and horizontal GRF traces for walking and running.](image)

**Figure 5:** Example vertical and horizontal GRF (BW) traces for walking (left) and running (right). (Farley & Ferris, 1998).
I accept hypothesis F2; the peak braking GRF of the push-foot was smaller than the peak propulsive GRF at all speeds. At all speeds tested, brakers exerted peak braking GRF that were on average 73% smaller than their peak propulsive GRF. At faster speeds, brakers used increased peak braking (GRF$_y$ = -0.038v - 0.03) (GRF in BW and v in m*sec$^{-1}$) (p<0.05) and propulsive forces (GRF$_y$ = 0.054v + 0.04) (GRF in BW and v in m*sec$^{-1}$) (p<0.05) (Table 1). Non-brakers simply did not exert braking forces so the propulsive GRF was greater by default but as non-brakers skateboarded faster they exerted greater, peak propulsive forces (GRF = 0.04v + 0.019) (p<0.05). Overall brakers exerted much greater magnitudes of peak propulsive force than the non-brakers at every velocity. 

I accept hypothesis K1 because both brakers and non-brakers significantly increased stride lengths at faster velocities. On average, brakers (SF=-0.115v +1.38) (SF in Hz and v in m*sec$^{-1}$) (p<0.05) exhibited slower stride frequencies compared to non-brakers (SF=-0.112v+1.88)(p<0.05) (SF in Hz and v in m*sec$^{-1}$) at all speeds tested (Fig 3a). Subjects commented that the fastest speed tested (4m/s) was slightly slower than their typical commute speed. This concurs with Board and Browning (2014) whose subjects averaged a typical overground commuting speed of ~4.5m* s$^{-1}$.

The average corresponding stride lengths of the brakers were substantially longer than the non-brakers at all speeds (Fig 3b). For comparison, at 1.25m*sec$^{-1}$ the average stride length of brakers was 1.04m, non-brakers was 0.72m and Nilsson and Thorstensson (1989) report 1.04m for walking. However, note that a skateboard stride has only one leg movement while bipedal gait stride has two leg movements. At 3.0m*sec$^{-1}$ the average stride length for brakers was 2.96m, non-brakers was 2.07m and Gottschall and Kram (2005) report 2.07m for running. Thus I partially accept hypothesis K2 that the stride lengths in skateboarding would be greater than walking or running at equivalent speeds.
I partially accept hypothesis E1 which stated that skateboarding would require less energy compared to walking and running. The rates of oxygen consumption for skateboarding (brakers and non-brakers) were not statistically different from walking 1.25m*sec\(^{-1}\) (p=0.30). However, for skateboarding at 3.0m*sec\(^{-1}\) the average rate of oxygen consumption was only about half that of running (p<0.05) (Fig 4). There were no differences in oxygen consumption rates between brakers and non-brakers at either 1.25m*sec\(^{-1}\) (p=0.15) or 3.0m*sec\(^{-1}\) (p=0.10). Overall, I reject the hypothesis that skateboarding would be metabolically cheaper than walking, but I accept the hypothesis that skateboarding would be metabolically cheaper than running. This may explain why skateboarders prefer to walk with their friends at slower speeds but if time is of the essence, skateboarding offers a faster velocity at a reduced metabolic cost compared to running.

I was surprised by the two distinctly different patterns of skateboarding forces: brakers and non-brakers. Post-hoc, I noted that five of the six brakers were Regular-footed and all of the non-brakers (n=5) positioned their right foot on the board (i.e. they used the Goofy configuration). Brakers were far more consistent from stride-to-stride than non-brakers as evident by the smaller standard deviations in the averages (Table 1). I did not determine hand dominance nor leg dominance in this study, but they should be measured in future research on skateboarding.

In general, the non-brakers used a higher stride frequency with smaller forces (vertical and propulsive). I did notice that during data collection, most Regular-footed subjects contacted the treadmill with their heels while non-brakers exhibited midfoot striking. I propose that the differences between these two forms of contact in skateboarding are analogous to the classification of rearfoot and midfoot strike patterns that Cavanagh and Lafortune (1980) first proposed for running. There are two distinct patterns in skateboard GRFs between being Regular or Goofy-footed that need to be investigated further.
To my knowledge, there are no other published GRF data for skateboarding to compare with my findings, so instead I will compare the GRFs of skateboarding to other forms of locomotion. Brakers demonstrated vertical peak magnitudes (1.552 BW) at 4.0 m*sec⁻¹ while the non-brakers demonstrated half of the magnitude (0.723±0.49BW) at 4.0 m*sec⁻¹. People running at 4.0 m*sec⁻¹ demonstrate a peak vertical ground reaction force of 2.72 BW (Munro and Miller, 1987). Thus, skateboarding utilizes much smaller vertical forces than running.

For comparison, the diagonal stride technique of cross-country roller skiing without poles, at 1.25 and 3.0 m*sec⁻¹, the average peak vertical ground reaction forces produced at the legs are between 0.91 and 1.19 BW (Kehler et al., 2014). At the same speeds, skateboarding brakers had similar vertical ground reaction forces with their push-foot of 0.91±0.20 and 1.32±0.30 BW respectively, while the non-brakers’ vertical ground reaction forces were considerably smaller (< half) at 0.43±.30 and 0.60±.40 BW.

In terms of stride kinematics, Board and Browning (2014) compared skateboarding overground at three different, self-selected speeds: slow, typical and fast. The mean averages were 3.7, 4.5, and 5.1 m*sec⁻¹, respectively with stride frequencies of 0.30, 0.41, and 0.54Hz. The stride frequencies at 4.00 m*sec⁻¹ that I measured were as much as five times faster (brakers=0.89 Hz ± 0.29, non-brakers=1.55Hz ± 0.25) than those reported by Board and Browning (0.3Hz). The difference is likely due to the fact that I tested on a treadmill while Board and Browning tested overground. Unlike during overground skateboarding, on a treadmill, subjects are constrained by the length of the treadmill deck and constant velocity which limits the propulsive/acceleration and coasting phases. An important next research topic is to investigate the differences between treadmill and overground skateboarding, which I have begun to do via an electronically instrumented skateboard.

Metabolically, skateboarding costs were: similar to walking, less than running, similar to classic XC roller skiing, but significantly greater than cycling at comparable speeds. Since I found no differences
between brakers and non-brakers in terms of metabolic costs, I have pooled their metabolic data for making comparisons with other modes of locomotion. All of the velocities tested by Board and Browning (2014) were faster than what we measured and they found that skateboarding at 3.7, 4.5 and 5.1 m*sec \(^{-1}\) had a mean oxygen consumption rates of 24.1, 29.1, and 37.2 mL*kg\(^{-1}\)*min\(^{-1}\) respectively. In my study, skateboarders on the treadmill at 3.0 m*sec\(^{-1}\) had a mean oxygen consumption of 21.6 mL*kg\(^{-1}\)*min\(^{-1}\). My results concur with a linear extrapolation of the results from Board and Browning’s data (2014) (Figure 6). I speculate that the difference between Board and Browning’s data and my data for metabolic cost could be due to the different gaits (i.e. steady vs. pulsatile), the presence of air resistance only during overground skateboarding, and/or different rolling resistances for treadmill belts versus asphalt. My metabolic results from skateboarding on a treadmill were similar to classic cross-country skiing on a treadmill (either diagonal stride or double poling technique). To allow comparison, I converted my data for oxygen consumption into J*kg\(^{-1}\)*m\(^{-1}\) by using the conversion factor of 20.1 Joules per mL of O\(_2\) (Taylor et al., 1980). Skateboarding had a cost of transport (COT) at 3.0 m*sec\(^{-1}\) of 4.22±0.29 J*kg\(^{-1}\)*m\(^{-1}\) while diagonal stride XC skiing has a COT at 3.0 m*sec\(^{-1}\) of 4-5 J*kg\(^{-1}\)*m\(^{-1}\) (Pellegrini et al., 2013). However compared to cycling, skateboarding involves a greater COT. Minetti et al. (2001) found that when riding a modern bicycle at 4m/s, a faster velocity, the COT was 0.7 J*kg\(^{-1}\)*m\(^{-1}\) and riding a racing bike had an even lower value of 0.5 Joules*kg\(^{-1}\)*m\(^{-1}\). As noted by Vance Tucker many years ago (1975), a person on a bicycle is the most efficient traveler in nature.
Figure 6: Rates of O$_2$ consumption versus velocity from the present study (circles) and Board and Browning (squares) (2014). The combined data set for skateboarding suggests a positive linear relationship between metabolic cost and velocity.

There were a few limitations to my skateboarding study to consider. I did not record GRF of walking or running in the same subjects and instead compared my skateboarding GRF data to literature values. However, the values found in the literature have been verified and replicated many times. The biggest limitation was the dimensions of the treadmill’s length (191cm) and width (51cm). The instrumented treadmill was invaluable for isolating the push-foot from the board-foot; however subjects were constrained to a treadmill length (1.91m) that prevented the typical acceleration and coasting phases observed in overground skateboarding. In overground skateboarding, skateboarders apply a number of pushes to accelerate up to a certain velocity then coast to a minimum velocity. On the treadmill, subjects were restricted by the need to maintain a nearly constant velocity.

Future studies of skateboarding should take into consideration the differences between brakers and non-brakers, treadmill and overground and different types of wheel-board mounting options that change the height of board-foot relative to the ground. In my study, the dominant majority of braking subjects (5 of 6) were Regular-footed and non-braking subjects (5 of 5) were Goofy-footed. Further studies should investigate the interactions between hand/leg dominance, Regular/Goofy configurations,
and braking/non-braking GRF patterns. Motion capture would be useful for quantifying the differences in technique between brakers and non-brakers. Due to the velocity fluctuations in overground skateboarding and constant velocity restriction on the treadmill it is reasonable to assume that the stride kinematics would be different between the two conditions. A tachometer device that converts wheel revolution frequency into velocity would be very useful in resolving the differences in stride frequency and stride length between overground and treadmill conditions. By obtaining the instantaneous velocities, researchers would be able to better quantify the pulsatile stride kinematic patterns.

The skateboarding industry is continually developing new board designs and mounting options. In my study, I had the subjects skate with their own preferred board and wheel-board mounting setup to minimize any unfamiliarity. Skateboarding setups have four main wheel mounted designs: top-mount, drop-through, lowered, or a combination of a drop-through and lowered with the former having the board-foot at the highest height and the later at the lowest (Figure 7). Professional skateboarders prefer to use the double drop setup for longer travelling very long distances while the top mount option is more widely used in slalom or downhill disciplines. The biomechanical differences have not been quantified for these four heights.

![Figure 7: The four different mounting options for a skateboard. Top mount being the highest and combining the drop-through and lowered for a double-drop option for the lowest (http://randal.com/faq/)](http://randal.com/faq/)
To summarize, skateboarders demonstrated two distinct GRF patterns: brakers and non-brakers. The vertical GRFs of both brakers’ and non-brakers’ push-feet were similar in shape to running, but of much lower magnitude than running. Skateboarding is a unique form of transportation in that stride frequency decreases at faster velocities. The energetic cost of skateboarding is equal to walking at 1.25 m*sec⁻¹ and about half that of running.
Chapter 5: Bibliography


