Ground reaction forces and loading rates associated with parkour drop landings from varying heights. [unpublished]

Damien L. Puddle BSpExSc

Centre for Sport and Exercise Science, Wintec, Hamilton, New Zealand

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ABSTRACT

Purpose: To explore and compare the maximal vertical ground reaction forces, loading rates and time to maximal vertical ground reaction forces associated with two Parkour techniques from varying heights.

Methods: Traceurs (n=12) performed precision (x5) and roll (x5) trials from each of three body heights (50%, 75% and 100%) from an adjustable platform onto a force plate. Maximal vertical ground reaction force, loading rate and time to maximal vertical ground reaction force were recorded for each landing.

Results: Height increases result in increases in maximal vertical force, time to maximal vertical force and loading rate (p<0.05). Roll landings consistently produce less maximal vertical force than precision landings from all body heights (-7.5%, -2.2% and -10.3% from 50%, 75% and 100% body height respectively) though statistical significance (p>0.05) was not reached. The majority of differences between techniques for time to maximal vertical force and loading rate were inconclusive. One significant difference (p=0.046) between precisions and rolls at 100% body height was seen for TmVF (change in mean of -30.3%).

Conclusion: Traceurs should be prepared to adapt their landings and their training to account for increased magnitudes imposed on their bodies during landings from increasing heights, in both roll and precision landings. Traceurs should continue to use their landing methods but experiment with greater emphasis on roll landing during training as this may result in clearer outcomes found in future research.

CERTIFICATE OF DISSERTATION

I Damien Puddle certify that all experimental work, results, analyses and conclusions reported in this dissertation are entirely my own effort except were otherwise acknowledged. I also certify that the work is original and has not been submitted for any other award.

 November, 2011

DEFINITION OF TERMS

Parkour – Parkour is a non-competitive movement based discipline focusing on safe and effective navigation of the given environment, governed by the notions of reach and escape, encapsulated by a philosophy of longevity and altruism.

Traceur – A male practitioner of Parkour, French. Female practitioners are called traceuses. In this study, where the male term is used the female is implied (except in direct reference to the studies participants).

Precision – landing on the forefoot/balls of the feet, bending the knees to absorb impact and using the arms to counterbalance the movement. The heels do not touch the ground.

Roll – a roll over the shoulder in the direction of travel, leading with one side of the body and finishing on the opposite side of the body. These rolls are initiated out of an initial forefoot landing and used when landing from height.

ABBREVIATIONS

GRF – ground reaction force

vGRF – vertical ground reaction force

mVF – maximal vertical ground reaction force

TmVF – time to maximal vertical ground reaction force

LR – loading rate

INTRODUCTION

Parkour is a non-competitive physical discipline and philosophy created by David Belle in the late 1980’s in Lisses, a small Parisian suburb in France (Marshall, 2010). In Parkour, male and female practitioners, or traceurs and traceuses (Thomson, 2008) - named for the way they trace a line through the environment (Bavinton, 2007) - aim to adapt their movement and their thinking to overcome physical and psychological obstacles in the particular environment they find themselves in (Hilscher & Heitlager, 2006). They attempt to act in a manner that would be used when trying to get somewhere or to someone, or away from somewhere or someone and in such a way redefine space and turn confining elements of structure into opportunities (Daskalaki, Stara, & Miguel, 2008).

The idea of changing ones movement to match ones environment opens the door to an extremely wide array of physical manoeuvres, including (but not limited to), running, jumping, vaulting, balancing, climbing, swinging, rolling and moving quadrupedally (on all four limbs). The emergence of Parkour has unlocked an abundance of opportunities for researchers to explore, but in the realm of research, Parkour is still in its formative years. The paucity of Parkour research is highlighted by McLean, Houshian, and Pike (2006) who stated that at the time of publication, their case study of a paediatric fracture sustained while practicing Parkour was the only one in medical literature. The New Zealand Parkour community and in fact the global community would benefit greatly from research. Studies investigating the benefits and harms associated with the movements involved in the practice of Parkour would be especially valuable as Parkour focuses on refining many of the building blocks of movement present in most other sporting activities and movements in everyday life.

Parkour is not just the completed product seen in mainstream media today, it is a journey and even a way of life (Saville, 2008). That means that even without the prospect of competition, external rewards and other accolades, training is extremely important as it shapes the life of the practicing individual and develops character. An integral part of this training is the practice of safe landing techniques which requires much attention. When landing from reasonable heights (below head height) a precision landing (a forefoot landing without heel contact) is commonly performed. Above head height, traceurs typically opt for a roll landing as it is thought to dissipate ground reaction forces upon landing, more so than the precision landing. From a height of 75cm, no significant differences were found between Parkour rolls and precisions (Puddle & Maulder, 2010). The findings established by Puddle and Maulder (2010) prompts the suggestion that the height used in their investigation was not a realistic height from which traceurs typically perform roll landings from. It was proposed that the utilisation of higher and multiple heights would allow for greater comparisons to be made between the two Parkour landing techniques and for larger differences to be seen between the variables of interest. They hypothesised that the trends in their data that supported the roll technique over the precision technique would achieve greater significance when investigated from a higher drop.

Statement of Purpose

The purpose of this study was to investigate and compare the maximal vertical ground reaction force, loading rate, and time to maximum vertical ground reaction force, in Parkour rolls and precisions from varying heights.

Hypothesis

It was hypothesised that as drop height increases, maximum vertical ground reaction force would increase, loading rate would increase, and time to maximum vertical ground reaction force would decrease. It was also hypothesised that the roll landing would have lower maximum vertical ground reaction force and loading rate magnitudes with slower times to maximum vertical ground reaction force than the precision landing.

LITERATURE REVIEW

The purpose of this research is to investigate the maximum vertical ground reaction force (mVF), loading rate (LR) and time to maximum vertical ground reaction force (TmVF) present during the execution of Parkour precision and roll landings from varying heights. It is therefore the purpose of this literature review to present findings from studies that have examined these kinetic variables of interest with reference to changes in height. Particular interest will also be placed on studies involving kinematics, such as different landing techniques, specifically those surrounding foot placement and breakfalling (fall arrest strategies).

Methodology

A thorough review of literature pertaining to drop landing with reference to height and technique differences was performed. Searches were conducted through SportDISCUS, ScienceDirect, OvidSP, the International Society of Biomechanics in Sport conference archives, Google Scholar and direct journals including the Journal of Applied Biomechanics and Sports Biomechanics. The following search terms: “drop landing”, “ground reaction forces”, “landing from height” and “breakfall” were utilised. From this search, 32 studies were chosen for final review.

Studies (or portions of studies) with data pertaining to women and children or data pooled from men and women and children were omitted from this review. The results from those studies were not comparable to the current study (where only male participants were examined) as variation between results may be due to sex or age differences. Similarly, units of measurements were altered to conform to the most popular method among the reviewed articles (BW for mVF and BW/s for LR) where possible.

Data Variation between Heights

In the literature, landing from height is tested using a number of protocols. The most common (and most applicable to the current study) is box drop landing, where participants drop from different sized or adjustable boxes/platforms situated beside a force plate. Two other methods of testing include vertical jump landing (or other jump technique), where the participant starts on the force plate and lands back on the force plate (Elvin, Elvin, Arnoczkey, & Torry, 2007; Gross & Nelson, 1988; McClay et al., 1994) and dropping from a bar suspended above a force plate (Clowers, 2002; Self & Paine, 2001).

Vertical Ground Reaction Forces

Articles in this section have been split into those whose investigation involved multiple drop heights (Table 1) and those that have only a single drop height (Table 2). Multiple height studies are typically investigating the change of variables with respect to variations in height while single height studies tend to focus on different landing strategies, investigate multiple variables, make correlations between those variables or collect normative data.

Within the area of drop landing, diverse athletic populations have been studied: University students (Kovacs et al., 1999), physically active individuals (Elvin et al., 2007), court sport athletes (Decker, Torry, Wyland, Sterett, & Steadman, 2003), elite volleyball players (Bisseling, Hof, Bredeweg, Zwerver, & Mulder, 2007), NBA players (McClay et al., 1994), gymnasts (McNitt-Gray, 1991) and paratroopers (Whitting, Steele, Jaffrey, & Munro, 2007). Selections of these populations have been compared within studies. For example, recreational athletes and gymnasts were tested against each other and findings showed that from heights of 32, 72 and 128cm gymnasts landed with reduced magnitudes (3.9 and 6.3 BW vs. 4.2 and 6.4 BW) at the first two heights but recreational athletes landed with lower vGRF at 128cm (9.1 vs. 11.0 BW) (McNitt-Gray, 1991). The authors hypothesised that this was due to reduced hip flexion, a reflection of the obligatory restraints upon gymnasts during competition. It also suggests that ingrained behaviours such as these may be evident when drop height is similar to that experienced in the tested athletes chosen field.

Of the 32 studies reviewed, seven of them used a landing protocol where one leg landed on the force plate and the other leg landed beside the force plate (all other studies had participants landing with both feet on the force plate or a foot on its own force plate). This type of protocol could result in asymmetrical landings based on the technique and physical profile/capabilities of the participants. Dufek and Bates (1990) acknowledged the possibility of asymmetrical landings and attempted to control for them through visual inspection. Of the seven studies using this landing protocol, this is the only mention of asymmetrical control. It is unclear whether the researchers in any of these six studies (including Dufek and Bates, (1990)) provide the single leg data or attempt to double it to reflect a whole body impact. This limitation in the literature causes inconsistencies when attempting to compare studies as results differ widely between studies using this protocol. This is particularly reflected by evaluating the differences between Bisseling, Hof, Bredewegm Zwerver and Mulder (2007), Zhang, Derrick, Evans and Yu (2008) and Dufek and Bates (1990) as depicted in Table 1.

Overall, studies investigating the changes in vGRF magnitude with reference to changes in height have found that increased drop heights consistently result in increased vGRF (see Table 1 for details). Researchers make it difficult for their studies to be compared however, as many of them have not made clear how they have presented their data (single leg magnitudes or otherwise).

Table 1. Tabulated literature review of varying height studies investigating vertical ground reaction forces (vGRF)

Author(s) and Year	Participants (n) (age - yrs, height - cm, mass - kg, experience - yrs)	Task Height Instructions	Results			
(Bisseling et al., 2007)	8 elite male volleyball players Age - 23.6 ± 2.5 Height - 189 ± 8 Mass - 84.5 ± 13.2 Experience - 5+	• Box drop landings • 30cm, 50cm, 70cm • One foot on force plate, landing as naturally as possible, looking forward • Peak vGRF (BW)	<u>30cm</u> 2.2 ± 0.7	<u>50cm</u> 2.8 ± 0.9	<u>70cm</u> 3.1 ± 0.9	
(Caster, 1998)	7 participants	• Box drop landings • 15cm, 30cm, 45cm, 60cm • Any manner appropriate • Max vGRF (N.Kg)	<u>15cm</u> 38.2 ± 4.3	<u>30cm</u> 49.8 ± 6.6	<u>45cm</u> 55.2 ± 4.8	<u>60cm</u> 64.9 ± 5.3
(Crowell et al., 1995)	Active duty SOF soldiers/soldiers going through SOF Qualification	• Box drop PLF landings • 107cm, 137cm, 171cm • Max vGRF (BW)	<u>107cm</u> <u>(4.57m/s)</u> 8.9	<u>137cm</u> <u>(5.18m/s)</u> 13.1	<u>171cm</u> <u>(5.79m/s)</u> 17.3	
(Dufek & Bates, 1990)	3 males involved in organised jumping sports Age - 27 to 30	• Box drop landings • 40cm, 60cm, 100cm • Toe-heel action required, one foot on the force plate • Max GRF (BW)	<u>40cm</u> F1 1.2 ± 0.5 F2 3.9 ± 1.0	<u>60cm</u> F1 1.3 ± 0.3 F2 4.0 ± 1.1	<u>100cm</u> F1 2.2 ± 0.3 F2 5.1 ± 1.3	

Table 1. Continued

Author(s) and Year	Participants (n) (age - yrs, height - cm, mass - kg, experience - yrs)	Task Height Instructions Unit of Measurement	Results		
(McNitt-Gray, 1991)	6 male gymnasts Height - 172.3 ± 2.3 Mass - 64.8 ± 3.1 6 male recreational athletes Height - 173.6 ± 5.0 Mass - 68.9 ± 5.5	• Box drop landings • 32cm, 72cm, 128cm • Preferred landing style, barefoot • Peak vGRF (BW)	<u>32cm</u> <u>Gymnasts</u> 3.9 ± 1.3 <u>Athletes</u> 4.2 ± 1.3	<u>72cm</u> <u>Gymnasts</u> 6.3 ± 1.9 <u>Athletes</u> 6.4 ± 1.7	<u>128cm</u> <u>Gymnasts</u> 11.0 ± 2.3 <u>Athletes</u> 9.1 ± 1.9
(Polsani, 2006)	15 male students Age - 23.9 ± 1.9 Height - 177.3 ± 5.5 Mass - 77.5 ± 8.2	• Box drop landings • 38.1cm, 50.8cm, 63.5cm • Arms side, arms front, arms crossed • Peak vGRF (BW)	<u>38.1cm</u> <u>Arms Side</u> 6.7 ± 1.7 <u>Arms Front</u> 7.2 ± 2.0 <u>Arms Crossed</u> 6.7 ± 2.1	<u>50.8cm</u> <u>Arms Side</u> 7.3 ± 2.0 <u>Arms Front</u> 8.0 ± 2.0 <u>Arms Crossed</u> 7.6 ± 1.7	<u>63.5cm</u> <u>Arms Side</u> 8.2 ± 2.0 <u>Arms Front</u> 8.6 ± 2.1 <u>Arms Crossed</u> 8.4 ± 1.9

Table 1. Continued

Author(s) and Year	Participants (n) (age - yrs, height - cm, mass - kg, experience - yrs)	Task Height Instructions Unit of Measurement	Results		
(Wang, 2009)	12 male physical education students Age - 22.0 ± 1.0 Height - 173.42 ± 4.37 Mass - 65.65 ± 7.07	• Box drop landings • 40cm, 60cm, 80cm • Hands on waist • Peak vGRF (BW)	<u>40cm</u> 1.5 ± 0.2	<u>60cm</u> 1.7 ± 0.2	<u>80cm</u> 2.1 ± 0.4
(Whitting et al., 2007)	20 Basic Parachute Course trained personnel Age - 32.0 ± 8.0 Height - 176.6 ± 7.3 Mass - 83.0 ± 10.2 Experience - 12 to 250 aerial descents	• Monorail drop PLF landings • 32cm, 74cm, 133cm • Standard PLF roll • Peak vGRF (BW)	<u>32cm</u> <u>(2.1m/s)</u> 5.8 ± 1.2	<u>74cm</u> <u>(3.3 m/s)</u> 9.3 ± 1.7	<u>133cm</u> <u>(4.6m/s)</u> 13.1 ± 2.6

Table 1. Continued

Author(s) and Year	Participants (n) (age - yrs, height - cm, mass - kg, experience - yrs)	Task Height Instructions Unit of Measurement	Results				
(Zhang, Bates, & Dufek, 2000)	9 physically active males Age - 25.0 ± 5.0 Mass - 74.4 ± 6.3	• Box drop landings • 32cm, 62cm, 103cm • Hands on buttocks • Max vGRF (N.Kg converted to BW)	<u>32cm</u> F1 0.8 ± 0.3 F2 2.6 ± 0.9 <u>SFL</u> F1 1.7 ± 1.0 F2 3.0 ± 1.1	<u>62cm</u> F1 1.8 ± 0.5 F2 3.3 ± 0.8 <u>NML</u> F1 1.9 ± 1.1 F2 3.4 ± 1.2	<u>103cm</u> F1 3.1 ± 0.3 F2 4.7 ± 1.0 <u>STL</u> F1 2.2 ± 1.1 F2 4.2 ± 1.2		
(Zhang et al., 2008)	10 physically active males Age - 23.5 ± 4.0 Height - 179 ± 1.0 Mass - 74.9 ± 10.1	• Box drop landings • 30cm, 45cm, 60cm, 75cm, 90cm • One foot on force plate • Peak vGRF (BW)	<u>30cm</u> F1 1.6 ± 0.4 F2 4.8 ± 1.7	<u>45cm</u> F1 2.3 ± 0.6 F2 5.0 ± 1.5	<u>60cm</u> F1 3.3 ± 0.9 F2 6.0 ± 1.4	<u>75cm</u> F1 4.2 ± 1.2 F2 6.7 ± 1.5	<u>90cm</u> F1 5.2 ± 1.3 F2 7.8 ± 2.1

Note: Information missing from table is respective of information missing from the reviewed article, vGRF = vertical ground reaction forces, S1 = subject 1, S2 = subject 2, S3 = subject 3, F1 = first peak, F2 = second peak, ~ = approximately.

Table 2. Tabulated literature review of single height studies investigating vertical ground reaction forces (vGRF)

Author(s) and Year	**Participants (n) (age - yrs, height - cm, mass - kg, experience - yrs)**	**Task Height Instructions Unit of Measurement**	**Results**			
(Blackburn & Padua, 2009)	20 Physically active males Age - 22.35 ± 2.25 Height - 180 ± 8 Mass - 86.05 ± 17.04	• Box drop landings • 60cm • Only one foot landing on the force plate • Peak vGRF (BW)	Preferred 4.4 ± 0.8	Flexed 3.8 ± 0.7		
(Clowers, 2002)	10 physically active males Age - 23.0 ± 3.0 Height - 180.0 ± 8.0 Mass - 74.0 ± 7.4	• Vertical bar drop landing • 60cm • One foot on force plate • Max vGRF (N.Kg, converted to BW)	Normal ~5.9 ± 0.5	Stiff ~7.9 ± 0.4	Stiff Flatfoot ~10.7 ± 0.8	Forefoot ~4.8 ± 0.3
(Decker et al., 2003)	12 male court sport athletes Age - 28.3 ± 3.9 Height - 180 ± 6.0 Mass - 81.8 ± 9.1 Experience - 5+ years	• Box drop landings • 60cm • Arms crossed, forefoot – rearfoot landings, one foot on force plate • Peak vGRF (BW)	F1 1.5 ± 0.4 F2 3.7 ± 0.9			

Table 2. Continued

Author(s) and Year	Participants (n) (age - yrs, height - cm, mass - kg, experience - yrs)	Task Height Instructions Unit of Measurement	Results	
(Gittoes & Kerwin, 2008)	Four-segment, angle-driven simulation model based off 2 performers Mass - 56.8 and 69.0	• Box drop landings • 46cm • Self selected strategies • Peak vGRF (BW)	<u>Performer 1</u> A – 4.9 B – 3.9	<u>Performer 2</u> A – 7.4 B – 4.8
(Gross & Nelson, 1988)	11 male basketball players	• Barefoot vertical jump landings • 90% vertical jump height • Peak vGRF (BW)	<u>Heel Contact</u> F1 – 2.0 F2 – 5.0	<u>No Heel Contact</u> F1 – 2.1 F2 – 3.8
(Kovacs et al., 1999)	10 male university students Age - 23.5 ± 2.5 Height - 185.0 ± 6.0 Mass - 82.5 ± 4.6	• Box drop landings • 40cm • Hands on hips • Peak vGRF (BW)	<u>Forefoot Only</u> F1 ~3.0 ± 1.1 F2 ~6.2 ± 2.2	<u>Heel-Toe</u> F1 ~10.1 ± 2.0 F2 ~4.3 ± 0.9
(McNair & Prapavessis, 1999)	154 male students Age - 16.1 ± 1.3	• Box drop landing • 30cm • Minimise the stress of landing • Peak vGRF (BW)	4.5 ± 1.7	

Table 2. Continued

Author(s) and Year	Participants (n) (age - yrs, height - cm, mass - kg, experience - yrs)	Task Height Instructions Unit of Measurement	Results			
(McClay et al., 1994)	24 male NBA players	• Jump landings (layup, jump shot, vertical jump) • Jump height • Peak vGRF (BW)	Lay-Up F1 8.9 ± 2.8 F2 2.8 ± 0.5	Jump Shot F1 6.0 ± 1.4 F2 2.0 ± 0.8	Vertical Jump F1 4.3 ± 1.2 F2 1.3 ± 0.4	
(Self & Paine, 2001)	Age – 29.0 ± 4.7 Height – 175.5 ± 5.5 Mass – 73.7 ± 9.5	• Vertical bar drop landing • 30.48cm • One foot landing on the force plate, arms over head. • Max vGRF (BW)	BN 4.3	SN 5.8	SP 4.1	SH 6.7

Table 2. Continued

Author(s) and Year	Participants (n) (age - yrs, height - cm, mass - kg, experience - yrs)	Task Height Instructions Unit of Measurement	Results	
(Walsh, Waters, & Kersting, 2007)	13 National Collegiate Athletic Association Division I basketball players. No instruction Age - 19.8 ± 0.9 Height -194.8 ± 11.3 Mass - 94.7 ± 1.9 Instruction Age - 19.6 ± 1.4 Height - 198.6 ± 7.0 Mass - 101.3 ± 15.2	• Box drop jumps • 30.5cm • "Drop from the platform, landing as soft as you can with your knees already bent at landing, then jump up as high as you can" • Peak vGRF (BW)	<u>No Instruction</u> Pre 9.6 ± 2.9 Post 10.0 ± 3.5	<u>Instruction</u> Pre 7.8 ± 3.7 Post 7.0 ± 1.8

Note: Information missing from table is respective of information missing from the reviewed article, vGRF = vertical ground reaction forces, S1 = scenario 1, S2 = scenario 2, S3 = scenario 3, F1 = first peak, F2 = second peak, ~ = approximately.

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Loading Rate

Another important variable for consideration in drop landing studies is loading rate (LR). LR is defined as the rate at which vGRF is applied per unit of time (Woodard, James, & Messier, 1999) or the speed at which the vGRF travels through the body. Woodard et al, (1999) speculate that the LR may be more important than the vGRF itself as it has been linked to the formation and advancement of musculoskeletal pathology.

The literature surrounding LR in drop landing is minimal at best (Table 3), but the findings show some interesting patterns. It appears that LR follows the same pattern as vGRF and increases in magnitude alongside increases in height – 32 ± 7 BW/s from 40cm, 35 ± 8 BW/s from 60cm and 55 ± 16 BW/s from 80cm (Wang, 2009). It is even more interesting to note that there are even larger differences between the LR of different landing techniques. Clowers (2002) investigated four different landing postures based on stiffness and foot placement. The results showed that from a 60cm drop, LR from approximately 151 ± 27 BW/s occurs in normal landings, increases to 213 ± 41 BW/s in stiff landings, 529 ± 149 BW/s in stiff-flatfoot landings, while forefoot landings resulted in the lowest BW/s at 88 ± 9. In Parkour, LR magnitudes from 75cm have been recorded as 84 ± 80 in forefoot only landings, 64 ± 60 in roll landings and 154 ± 96 in traditional (forefoot – rearfoot) landings (Puddle & Maulder, 2010).

Few authors seem to have investigated this idea to great depth in drop landing research, outlined by the fact that even when included as a variable, it is only presented but not actually discussed in three of the four studies in Table 3. Future research should make serious considerations about the inclusion of LR in drop landing studies because of its implications on health.

Table 3. Tabulated literature review, loading rate

Author(s) and Year	Participants (n) (age - yrs, height - cm, mass - kg, experience - yrs)	Task Height Instructions	Results (loading rate in BW/s)			
(Clowers, 2002)	10 physically active males Age - 23.0 ± 3.0 Height - 180.0 ± 8.0 Mass - 74.0 ± 7.4	• Vertical bar drop landing • 60cm • One foot on force plate	<u>Normal</u> ~151 ± 27	<u>Stiff</u> ~213 ± 41	<u>Stiff Flatfoot</u> ~529 ± 149	<u>Forefoot</u> ~88 ± 9
(Decker et al., 2003)	12 male court sport athletes Age - 28.3 ± 3.9 Height - 180 ± 6.0 Mass - 81.8 ± 9.1 Experience - 5+ years	• Box drop landings • 60cm • Arms crossed, one foot on force plate	F1 - 162 ± 61 F2 - 102 ± 48			
(Gittoes & Kerwin, 2008)	Four-segment, angle-driven simulation model based off 2 performers Age - 22 and 24 Mass - 56.8 and 69.0	• Box drop landings • 46cm • Self selected strategies	<u>Performer A</u> A - 70 B - 65	<u>Performer B</u> A - 112 B - 58		
(Wang, 2009)	12 male physical education students Age - 22.0 ± 1.0 Height - 173.42 ± 4.37 Mass - 65.65 ± 7.07	• Box drop landings • 40cm, 60cm, 80cm • Hands on waist	<u>40cm</u> 32 ± 7	<u>60cm</u> 35 ± 8	<u>80cm</u> 55 ± 16	

Note: Information missing from table is respective of information missing from the reviewed article, BW/s = bodyweights per second, F1 = first peak, F2 = second peak, ~ = approximately.

Time to Peak or Maximum Vertical Ground Reaction Force

The time to peak or maximum vertical ground reaction force (TmVF) is an extremely important variable to include in drop landing studies because passive forces or forces speculated to cause injury, reach their peak in less than 50ms (Ricard & Veatch, 1990). This means that any study investigating forces, especially drop landing, should be including a temporal variable so that researchers can make suggestions on possibly injurious landing heights/techniques. Unfortunately, few drop landing articles have researched this and several who have, do not discuss the potentially injurious effects of their results.

As indicated in Table 4, recreationally active males have been found to reach peak vGRF at 40ms (±10.3) when utilising a forefoot to rearfoot landing after dropping from a 60cm height (Decker et al., 2003). Students from a university physical education department landed with peak vGRF at 51 ± 12 ms from 40cm, 52 ± 12 ms from 60cm and 41 ± 8 ms from 80cm (Wang, 2009). Male university students dropping from a height of 40cm and landing with forefoot only and heel-toe techniques reached peak vGRF in 85ms and 15ms respectively (Kovacs et al., 1999). Decker et al (2003) and Wang (2009) had almost identical results from 60cm, but Kovacs et al (1999) had a substantially longer time to peak vGRF than Wang (2009) from 40cm which may have been caused by the difference in landing technique but cannot be confirmed because Wang did not clarify landing technique beyond “hands on hips”. Researchers should always clarify what landings were performed by their participants so comparisons and statements can be made accurately.

Forefoot-rearfoot landings might potentially result in harmful TmVF based on the above findings. In 2010, Puddle and Maulder discovered that forefoot-rearfoot landings performed by traceurs resulted in TmVF of 40 ± 20 ms and that their own landing techniques (forefoot only and rolls) resulted in TmVF of 80 ± 50 ms and 80 ± 30 ms respectively.

Therefore, it may be possible to increase the TmVF and reduce harm by performing forefoot only landings.

TmVF is calculated by subtracting the time at peak/maximal vGRF by the time at initial contact. Many studies discuss initial contact or TmVF, but few studies actually state when initial contact occurred or how this variable was calculated. The few that have defined it have explained it as the time at which force magnitudes exceed 10N (Fong, Blackburn, Norcross, McGrath, & Padua, 2011), 15N (Cortes et al., 2007) or 50N (Cronin, Bressel, & Finn, 2008; McClay et al., 1994). This highlights how important it is to ensure the minimum signal that is accepted as a vGRF is reported so that data can be compared between studies (Munro, Miller, & Fuglevand, 1987).

Table 4. Tabulated literature review, time to peak vertical ground reaction force

Author(s) and Year	Participants (n) (age - yrs, height - cm, mass - kg, experience - yrs)	Task Height Instructions	Results (time to peak/max vGRF in ms)		
(Decker et al., 2003)	12 male court sport athletes Age - 28.3 ± 3.9 Height - 180 ± 6.0 Mass - 81.8 ± 9.1 Experience - 5+ years	• Box drop landings • 60cm • Arms crossed, one foot on force plate	F1 -10 ± 4 F2 - 40 ± 10		
(Kovacs et al., 1999)	10 male university students Age - 23.5 ± 2.5 Height - 185.0 ± 6.0 Mass - 82.5 ± 4.6	• Box drop landings • 40cm • Hands on hips	Forefoot Only F1 - 17 ± 3 F2 - 68 ± 25	Heel-Toe F1 - 15 ± 2 F2 - 89 ± 29	
(Wang, 2009)	12 male physical education students Age - 22.0 ± 1.0 Height - 173.42 ± 4.37 Mass - 65.65 ± 7.07	• Box drop landings • 40cm, 60cm, 80cm • Hands on waist	40cm 51 ± 12	60cm 52 ± 12	80cm 41 ± 8

Note: Information missing from table is respective of information missing from the reviewed article, F1 = first peak, F2 = second peak.

Data Variation between Techniques

Soft and stiff landings

Kinematics and kinetics are tightly linked. In the literature, greater degrees of flexion at the ankle, hip and especially the knee are characteristic of a "soft" landing whereas less flexion (more extension) results in a more erect posture and is referred to as a "stiff" landing. It has been hypothesised that the body modulates to increased demands by employing a softer landing (Wang, 2009) and does occur in recreationally active individuals as they employ landing strategies with increased knee and hip flexion from increased heights (McNitt-Gray, 1991). Many studies have investigated the kinematic effects on landing kinetics and discovered that lower vGRFs are present during soft landings (Devita & Skelly, 1992; Dufek & Bates, 1990). For example, active flexion of the hip has shown reduced impact forces in physically active men (Blackburn & Padua, 2009) thus showing that soft landings result in lower vGRF than stiff landings.

Foot Placement

Few studies have looked at the effect of foot placement as part of landing technique and its affect on vGRF, but some remarkable results have been found by those that have. Peak forces seem to be reduced when landing from height in many sports by employing a forefoot-rearfoot landing (Frederick, Determan, Whittlesey, & Hamill, 2006). Indeed, research has shown that forefoot-rearfoot landings result in reduced vGRF compared to flatfoot landings (Dufek & Bates, 1990).

Force traces for vGRF are typically unimodal or have one peak for flatfoot, forefoot only and heel only landings, whereas forefoot-rearfoot landings are bimodal or have two peaks (Cronin et al., 2008). Except for one (McClay et al., 1994), all studies in this review where a forefoot-rearfoot landing technique was used by participants, the first peak from the forefoot contact is always lower in magnitude than the second peak from the rearfoot contact (Dufek & Bates, 1990; Gross & Nelson, 1988; McNitt-Gray, 1991; Polsani, 2006; Prapavessis & McNair, 1999; Walsh et al., 2007; Zhang et al., 2008).

Hip and knee flexion were both significantly less in forefoot-rearfoot contact than rearfoot-forefoot contact at the point of peak vGRF in a sample of university students, thus showing that forefoot-rearfoot landings have a more erect posture (Cortes et al., 2007). The impact magnitudes however, were not recorded and it cannot be said if the forefoot-rearfoot was still more beneficial than the rearfoot-forefoot technique despite the relative stiffness of the landing. Forefoot only landings allow for greater absorption with the use of the lower extremity musculature than rearfoot-forefoot landings (Kovacs et al., 1999), so it is possible that removing heel contact from landing strategies may increase lower extremity flexion or have other benefits causing reduced vGRF. Wobbling mass models have been used to simulate forefoot landings to investigate the sensitivity of loading experienced and specific timing of joint kinematic strategies (Gittoes, Kerwin, & Brewin, 2009). The authors conclude that their simulation showed that individuals may be able to attenuate the vGRF during forefoot landing due to the kinematic strategy employed but associated lower extremity kinematics may concurrently increase joint loading. The assumption made by Gitteos et al (2009) was based upon potentially unrealistic vGRF magnitudes (due to fluctuations in the time of ankle joint action) present in the landings performed by one of their participants and reduces the accuracy of the study's findings.

Forefoot only and forefoot-rearfoot techniques have been compared against other techniques or in isolation, but few researchers have matched them within a study. Gross and

Nelson (1988) investigated the role that the ankle has on shock attenuation during landing. They split their participant pool into two landing groups: forefoot-rearfoot and forefoot only. A comparison of the two styles indicates that both groups had forces of a similar magnitude at the point of initial contact, but those landing without heel contact had significantly less (22%) maximum force. Participants using the forefoot only landing, lowered their heels with greater control and produced smaller peak loads than those using the forefoot-rearfoot landing, making forefoot only landings an appealing method for preventing long term injury (Gross & Nelson, 1988). Unfortunately, exact values for the magnitudes cannot be presented as Gross and Nelson (1988) presented their findings in graph format without making specific reference to the numbers found therein. Puddle and Maulder (2010) investigated both these landings strategies within a population of traceurs and discovered magnitudes of 3.2 ± 0.2 BW in forefoot only landings compared with 5.2 ± 1.2 BW in forefoot-rearfoot landings, a 38.4% difference in force ($p = 0.0003$).

It appears that individuals are able to alter the vGRF experienced during landing by manipulating their posture both through different ranges of joint flexion and also the placement of their body relative to the ground (e.g. forefoot only contact).

Rolling and Fall Arresting (Breakfalling)

There are many types of rolling movements, including log rolls, shoulder rolls, forward rolls, side rolls and backward rolls (Ratliffe, 2000), which are present in well known activities such as martial arts, gymnastics and parachuting. Children love to perform rolling, flipping, tumbling and somersault movements (Ratliffe, 2000), but despite their love for rolls, many children are not competent in performing them. A study by Masser (1993) observed two major problems that children have when learning the forward roll. 1) They place their head on the floor when beginning; and 2) they open up as the roll over. Cues such as “tuck your head” and “grasp your shins as you roll over” were found to be ineffective at teaching first graders how to complete a successful forward roll. Masser (1993) therefore asked the question:

> “How is it that children pass through physical education programs yet fail to reach mature patterns in many of their fundamental motor skills?”

This statement suggests that rolling is a fundamental motor skill. In fact, the proper technique for falling is one of the most essential abilities that anyone can possess (Park & Seabourne, 1997). If a child does not learn a fundamental skill such as this (even when it is part of the physical education system), then it is unlikely that their adult counterparts will achieve this skill and since adults are stiffer and more inflexible than children, a fall could be disastrous for them (Park & Seabourne, 1997). Injuries due to falls can be reduced by two methods, reducing the amount of falls or reducing the severity of sustained impact (Lo & Ashton-Miller, 2008), yet even though anyone can fall at anytime, little is done to prepare the body for such an experience. Lo and Ashton-Miller (2008) presume that fall number cannot be reduced to zero, therefore the ability to arrest a fall while minimising injury risk is important (Sabick, Hay, Goel, & Banks, 1999). Elderly individuals are of particular risk of hip fracture during falls (Groen, Weerdesteyn, & Duysens, 2007) but falls are also the leading cause of accidental injuries in children, as cited by Sabick et al., (1999). DeGoede et al., (2003) suggest that insights gathered from fall-arrests in young athletes of certain sports may be beneficial in teaching the elderly to fall safely.

Fall arrest strategies in younger athletes and rolling (an apparent fundamental motor skill) have not been studied at length. The peak force experienced during dive-rolls (where the hands contact first) occurs when the upper back makes contact with the ground which means that the upper limbs are only necessary for partial deceleration (Davidson, Mahar, Chalmers, & Wilson, 2005). This has some relevance to traceurs as the dive roll is a common method of navigating obstacles and terrain. However, this technique is not often used in Parkour landings from height as the athletes speculate their upper limbs will experience severe loading upon contact. A roll landing, the integral part of safe landing in Parkour, was tested against a forefoot-rearfoot landing in a population of traceurs (Puddle & Maulder, 2010). Results showed that the roll landing had significantly lower vGRF (p=0.0001), loading rates (p=0.001) and slower times to max vGRF (p=0.009). These findings would suggest that active practice of rolling (present in Parkour training) is beneficial for safe landing strategies and could be useful for fall arrest strategies in other populations.

Parachute Landings

While many researchers are investigating falls in the elderly and infirm, other researchers are investigating breakfalling in some of the most able bodied individuals, paratroopers. The falls and techniques used for minimising injury risk in falls are all from standing height as that is what is applicable to the population. Paratroopers however are landing from significant heights above the ground and must learn how to touchdown safely, similar in many ways to traceurs.

Researchers acknowledge that different types of parachute result in variances between landing forces, but state that the magnitudes sustained are usually equivalent to those sustained when jumping off a wall of 9-12 feet high (Bricknell & Craig, 1999). Those magnitudes were not presented however and cannot be compared against the magnitudes incurred by the Parkour landing techniques.

Bricknell and Craig (1999) have discussed the early days of parachute training. Both Germans and Americans taught a forward roll technique over an outstretched arm; the attachment point of German parachutes meant that this was the only landing option. The British and American parachutes had attachment points on the top of each shoulder and the British created an alternative landing procedure involving a sideways roll. This was found to result in fewer injuries to combatants and was quickly adopted by other nations.

Nowadays, all paratroopers are taught the 5-point parachute landing fall (PLF) to minimise injury risk upon landing (Whitting et al., 2007). The PLF has minor differences between countries such as the Australian initial flatfoot contact and the American initial forefoot contact, but everything else is practically identical. The American PLF contact sequence:

> "(a) balls of the feet, (b) calf, (c) thigh, (d) buttocks and (e) lattisimus dorsi" (Crowell et al., 1995).

Even though this new method of landing is meant to reduce injuries, modern studies show that injuries during parachuting are still common with approximately 83.8% of injuries occurring during landing and 58% of injuries occurring in the lower extremities (Ellitsgaard, 1987).

Basic Parachute Course trained personal dropped from a custom designed free-wheeling trolley monorail onto a force plate and their landings were recorded (Table 1). Those that landed forefoot first into the PLF had greater knee and ankle flexion, lower peak forces and slower times to peak force (Whitting et al., 2007), suggesting that the American PLF adaptation is more beneficial than the Australian flatfooted method. As descent height and velocity increase, vGRF becomes significantly higher when performing PLF landings (Crowell et al., 1995; Whitting et al., 2007). It has also been shown that the landings of

Australian participants become increasingly more forefoot first rather than flatfoot, neglecting the Australian PLF variation (Whitting et al., 2007). Unfortunately, the majority of the articles in this review pertaining to parachute landings were from outside of the USA and it is unclear whether the Americans have reduced incidences of injury compared to other countries that may employ a more flatfoot approach like that of Australia.

Conclusion

The studies in this review consistently show that vertical ground reactions forces and loading rates increase concurrently with height but it is inconclusive whether time to vertical ground reaction force follows this same pattern. The utilisation of greater flexion coupled with forefoot first and even forefoot only landings reduces vertical ground reaction force in a range of athletic populations. Within this range however, very little information pertaining to the years of experience of the participants was included. While it may seem to be a less substantial piece of information to include within a study for some researchers, it is important to quantify experience as it will not only allow for greater comparisons between athletes of different sporting codes, but also between athletes of the same code.

Variations in height clearly results in variations in data. Varying techniques have the same result, yet many drop landing researchers have failed to define their landing parameters. Researchers should also be wary of making blanket statements/decisions that will affect the outcomes of their research (i.e. participants landed with their hands on their waist to ensure a natural landing action – this is not a natural landing position).

Conversely to the above limitation, some studies fail to make statements altogether. For example, several studies that have participants landing with both feet on the ground but only one foot on force plate (6 out of 32 reviewed articles) never state whether they double the results in an attempt to reflect “two footed” landings or whether they account for asymmetrical type landings. Similarly, some studies showed F1 and F2 peaks but others only referred to peak vGRF. It is assumed that these match the F2 of other studies, but this cannot be confirmed as it is not explained within the studies themselves. Ultimately, drop landing research is comprised of some very in depth and informative research but a lack of methodological specifics and the absence of some essential variables and discussion points reduce the credibility within the topic area.

METHODS

Experimental Procedure Overview: Participants

New Zealand based traceurs (n=12) were recruited for this study (see Table 5 for characteristics). A participant pool of 12 was beneficial in this study as it allowed for randomisation of trials for all participants and the findings of Bates, Dufek and Davis (1992) suggest that this study used adequate sample and trial sizes to achieve statistical power values of 90%. All participants were traceurs with at least 2 years of Parkour training experience, within the ages of 16-30 and free from lower limb injury. Participants were provided with an information sheet outlining the details of their involvement prior to participation in the current study. Those who agreed to participate signed a written consent form before participating. Ethical approval was sought for all procedures and granted by the HERC Ethics Committee at Wintec.

Table 5. Traceur characteristics

	Mean ± SD
Age (yrs)	22.5 ± 4.2
Height (cm)	180.5 ± 5.1
Weight (kg)	75.9 ± 9.9
Training (yrs)	3.5 ± 1.1

Experimental Procedures

The availability of skilled traceurs for this study was limited, reducing the population size of possible control and experimental groups. Therefore, this study utilised a time series experimental design whereby the participants acted as their own control (Hopkins, 2000).

All traceurs attended a familiarisation day where they performed trials of both landing techniques (precision landing and roll landing) from 50%, 70% and 100% of the average traceur body height. Following the familiarisation day all Traceurs attended a single testing day. On this testing day traceurs were randomly assigned a block randomised trial sequence (see Table 6).

Table 6. Block-randomised trial sequences

Participant #		% of Body Height		Condition
1, 7	100	50	75	A, B
2, 8	75	100	50	B, A
3, 9	50	75	100	A, B
4, 10	100	75	50	B, A
5, 11	75	50	100	A, B
6, 12	50	100	75	B, A

Note: Condition A = precision landings performed first, Condition B = roll landings performed first.

Before recording any trials, traceurs performed a warm-up involving five minutes of static cycling followed by self-directed dynamic stretching. Following their warm-up, traceurs performed five trials of both landing techniques at each of the three landing heights (Figures 1-3) for a total of 30 trials in all.

The dominant leg, or leading leg as it will be referred to hereafter, was determined during the familiarisation day. In the literature, the dominant limb is defined as the limb that is used in activities or leads out and the non-dominant limb is used for stability and postural support (Sadeghi, Allard, Prince, & Labelle, 2000). It was observed that Traceurs always led with the same leg when stepping from the platform. Therefore, this leading leg was recorded for each traceur and utilised during the testing day for all trials to ensure consistency.

Traceurs ascended the platform via a set of stands beside the platform and stood at the edge. At a cue from the researcher, traceurs stepped out with their leading leg without jumping up or crouching down and performed their allocated landing technique. Previous research attempted to control the step off by ensuring traceurs locked their non-leading leg while stepping out to stop crouching or jumping from occurring, however this was perceived as a limitation as traceurs were unaccustomed to this technique when training (Puddle & Maulder, 2010). In order for traceurs to feel comfortable with the step off protocol and still ensure control, they were told to step from the platform without crouching down or jumping up (Decker et al., 2003). Researchers then observed the traceurs as they stepped out from the platform and ruled trials as acceptable or unacceptable based on their ability to conform to this protocol. All five landings for a technique were performed consecutively before swapping to the five trials of the second technique.

The variability between athlete footwear is large. For this study, shoes (although required for participation) were not standardised. Participants wore their preferred training shoe for all familiarisation and testing procedures.

Between performances of a successful landing trial (landing was on the centre of the force plate and the correct technique was used), one minute rest periods were sustained. Three minutes of rest was given to traceurs between changes in landing heights.

Data Collection

Traceurs performed all their trials from an adjustable platform (SDJA1500 Manual Stacker). Wooden boxes were secured to the platform to achieve the height needed for some of the traceurs to drop from their 100% body height. The platform was situated 0.3m away from the embedded force plate (Kistler, Switzerland) to ensure adequate contact when stepping from the platform. The force plate was used to record all kinetic variables of interest and sampled at a rate of 1000Hz. BioWare 4.1 software was used to collect all the relevant data.

Data Analysis

Data extrapolation was achieved with the use of BioWare 4.1 software. Vertical ground reaction forces were low pass filtered using a fourth-order Butterworth filter with a 50 Hz cut-off frequency (Johnson & Buckley, 2001). Data was exported to Ms Excel 2007 where the variables of interest were examined. Definitions and calculations of these variables are located in Table 7 below.

Table 7. Variables of interest with definitions and calculations

Variable of Interest (Unit of Measurement)	**Definition**	**Calculation**
Maximal vertical ground reaction force (BW)	The highest peak of force recorded during landing.	Calculated via the force plate.
Loading rate (BW/s)	The speed at which forces impacted the body.	Calculated by dividing the maximal vertical force by the time to the maximal vertical force (Bauer, Fuchs, Smith, & Snow, 2001; Crossley, Bennell, Wrigley, & Oakes, 1999).
Time to maximal vertical ground reaction force (ms)	The time taken to reach the maximal vertical force from initial contact.	Calculated by subtracting the time at maximal vertical force by the time at initial contact (where the vertical force exceeded 50N (Cronin et al., 2008)).

Note: BW = bodyweight, ms = milliseconds, BW/s = bodyweight per second.

Figure 1. Adjustable platform at 50% body height.

Figure 2. Adjustable platform at 75% body height.

Figure 3. Adjustable platform at 100% body height.

Statistical Procedures

Comparisons were made for all three variables (mVF, LR and TmVF) in two categories: 1) within both techniques (precisions and rolls) across all three heights (50%, 75% and 100% body height) and 2) between techniques at all three heights.

All statistical procedures and comparisons were carried out using the methods of Hopkins (2006). This was achieved with the usage of MS Excel 2007 spreadsheets, performing post-only crossover analyses. These spreadsheets presented statistical outcomes in several formats, including *p* values ($p<0.05$ = significant), raw and percentage differences (with 90% confidence intervals of those differences) and Cohen's effect sizes.

Log transformation within the spreadsheets was used to ensure normal distribution of data and eliminated errors that could have been present from the raw variable of interest values (Batterham & Hopkins, 2006). In order to provide qualitative inferences for the differences between the landing heights and techniques, Cohen’s effect sizes were used. Those effect sizes are described with the use of the following scale: 0 – 0.2 trivial; 0.2 – 0.6 small: 0.6 – 1.2 moderate; 1.2 – 2.0 large; 2.0 – 4.0 very large. To increase the likelihood that the real effects would at least be small, an effect size of 0.2 (Cohen units) was chosen to be the smallest worthwhile difference (Cohen, 1990).

RESULTS

The findings for both landing techniques are presented as Mean ± SD in Table 8. Significant differences were found between landing heights for precisions (Table 9) and rolls (Table 10) in all three variables (with the exception of two calculations). No significant differences were found for the majority of the dependent variables (except one) between precisions and rolls at 50% body height, 75% body height or 100% body height (Table 11).

Table 8. Mean variable results from all three heights (mean ± SD)

	Precision			Roll		
	50%	**75%**	**100%**	**50%**	**75%**	**100%**
mVF (BW)	3.2 ± 0.3	4.8 ± 0.8	7.6 ± 1.5	3.0 ± 0.4	4.7 ± 1.0	7.0 ± 1.6
TmVF (ms)	61 ± 65	24 ± 13	21 ± 12	60 ± 19	21 ± 16	15 ± 13
LR (BW/s)	112 ± 77	336 ± 162	554 ± 274	75 ± 33	359 ± 151	630 ± 222

Note: % = of body height, mVF = maximum vertical ground reaction force, BW = bodyweight, TmVF = time to maximum vertical ground reaction force, ms = milliseconds.

Differences between Heights

Maximum Vertical Ground Reaction Force

Precision comparisons (Table 8) show that as height increases mVF increases significantly ($p<0.05$) between all three heights with change in mean values ranging from 45.3% to 132.4% and with very large effect sizes (4.60 to 10.36). Roll comparisons (Table 9) show a similar trend, with significant differences between all heights ($p<0.05$), change in mean percentage values from 50.2 to 130.7 with very large effect sizes (3.03 to 6.22).

Loading Rate

Loading rate differences between precision trials were significant in all comparisons (*p*<0.05) with large effect sizes for 50%-75% and 50%-100% and a small effect size for 75%-100%. Loading rate differences between roll trials were significant in all comparisons (*p*<0.05) with very large effect sizes for 50%-75% and 50%-100% and a moderate effect size for 50%-75%.

Time to Maximum Vertical Ground Reaction Force

Precision trials resulted in significantly faster TmVF (*p*<0.05) except from 75%-100% (*p*=0.169). The significant differences have change in mean values of -54.3% (50%-75%) and -61.3% (50%-100%) with moderate and large effect sizes respectively. Roll trials also result in significantly faster TmVF (*p*<0.05) except from 75%-100% (*p*=0.503). The significant differences have change in mean values of -70.5% (50%-75%) and -76.5% (50%-100%) with very large effect sizes.

Table 9. Differences in mechanical characteristics between heights for the precision task

	Comparison	Change in mean (%) with 90% confidence limit (lower ; upper limit)		Effect sizes	Qualitative inferences of effect sizes	*p* value
		Value	Range			
mVF (BW)	50% - 75%	45.3	36.6 ; 54.7	4.60	very large	<0.05*
	50% - 100%	132.4	108.2 ; 159.3	10.36	very large	<0.05*
	75% - 100%	59.9	39.6 ; 83.1	5.77	very large	<0.05*
TmVF (s)	50% - 75%	-54.3	-62.4 ; -44.4	-1.11	moderate	<0.05*
	50% - 100%	-61.3	-69.7 ; -50.6	-1.35	large	<0.05*
	75% - 100%	-15.4	-31.0 ; 3.8	-0.24	small	0.169
LR (BW/s)	50% - 75%	234.6	177.7 ; 303.1	1.40	large	<0.05*
	50% - 100%	446.2	320.9 ; 608.9	1.97	large	<0.05*
	75% - 100%	63.3	25.8 ; 111.8	0.57	small	0.006*

Note: mVF = maximum vertical ground reaction force, BW = bodyweight, TmVF = time to maximum vertical ground reaction force, s = seconds, * = significant difference (p<0.05), see Appendix A for exact *p* values.

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Table 10. Differences in mechanical characteristics between heights for the roll task

	Comparison	Change in mean (%) with 90% confidence limit (lower ; upper limit)		Effect sizes	Qualitative inferences of effect sizes	*p* value
		Value	Range			
mVF (BW)	50% - 75%	53.6	44.1 ; 63.7	3.19	very large	<0.05*
	50% - 100%	130.7	112.4 ; 150.5	6.22	very large	<0.05*
	75% - 100%	50.2	40.1 ; 61.0	3.03	very large	<0.05*
TmVF (s)	50% - 75%	-70.5	-79.0 ; -58.7	-3.11	very large	<0.05*
	50% - 100%	-76.5	-82.1 ; 69.1	-3.69	very large	<0.05*
	75% - 100%	-14.6	-42.6 ; 28.0	-0.39	small	0.503
LR (BW/s)	50% - 75%	358.6	253 ; 495.6	3.43	very large	<0.05*
	50% - 100%	709.5	491.2 ; 1008.3	4.71	very large	<0.05*
	75% - 100%	67	15.0 ; 141.5	1.16	moderate	0.030*

Note: mVF = maximum vertical ground reaction force, BW = bodyweight, TmVF = time to maximum vertical ground reaction force, s = seconds, * = significant difference (p<0.05), see Appendix A for exact p values.

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Differences between Techniques

There were no significant differences ($p>0.05$) between precisions and rolls at 50% body height despite a -7.5% change in mean for mVF, 21.4% for TmVF and -20.8% for LR. Similarly, there were no significant differences ($p>0.05$) between precisions and rolls at 70% body height. A change in mean of -2.2% was seen for mVF, -6.8% for TmVF and -21.7% for LR. One significant difference ($p=0.046$) between precisions and rolls at 100% body height was seen for TmVF (change in mean of -30.3%). Changes in mean for mVF and LR were -10.3% and 12.6% respectively.

Table 11. Differences between precisions and rolls from all three body heights

		Change in mean (%) with 90% confidence limit (lower ; upper limit)		Effect sizes	Qualitative inferences of effect sizes	*p* value
	Body Height	**Value**	**Range**			
mVF (BW)	50%	-7.5	-14.5 ; 0.2	-0.95	moderate	0.107
	75%	-2.2	11.8 ; 8.4	-0.12	trivial	0.704
	100%	-10.3	-21.3 ; 2.3	-0.50	small	0.165
TmVF (s)	50%	21.4	-8.2 ; 60.6	0.28	small	0.238
	75%	-6.8	-25.3 ; 16.4	-0.10	trivial	0.580
	100%	-30.3	-47.8 ; 7.1	-0.59	small	0.046*
LR (BW/s)	50%	-20.8	-43.6 ; 11.2	-0.27	small	0.244
	75%	-21.7	-41.7 ; 5.2	-0.44	small	0.165
	100%	12.6	-23.5 ; 65.9	0.17	trivial	0.587

Note: mVF = maximum vertical ground reaction force, BW = bodyweight, TmVF = time to maximum vertical ground reaction force, LR = loading rate, s = seconds * = significant difference (*p*<0.05).

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DISCUSSION

The purpose of this study was to investigate the maximal vertical ground reactions forces, loading rates and time to maximum vertical ground reaction forces present during Parkour precision and roll landing from varying heights.

It was hypothesised that an increase in height would see increases in both maximal vertical ground reaction force (mVF) and loading rate (LR), while time to maximal vertical ground reaction force (TmVF) would decrease. The findings confirmed this hypothesis with high statistical significant differences between body heights ($p<0.05$). It was further hypothesised that the roll landing would result in lower and thus more beneficial force and loading rate magnitudes with slower times, but results were not significant enough to be conclusive between the two techniques and consequently did not significantly favour either technique over the other.

Both landing techniques show extremely significant increases ($p<0.05$) in mVF between all three drop heights agreeing with this studies hypothesis. These findings are also in agreement with previous studies investigating multiple drop heights (McNitt-Gray, 1991; Whitting et al., 2007). The differences between 50% - 75% and 50% - 100% body height were very significant ($p<0.05$) for LR and TmVF for both techniques, but the differences between 75% - 100% were less significant for LR ($p=0.006$ for precisions, $p=0.030$ for rolls) and not significant for TmVF. The changes in TmVF and LR from 75% - 100% body height are markedly reduced compared with the changes from 50% - 75%. This relationship presents the idea that while TmVF continues to quicken and LR continues to increase after 75% body height, the body's ability to adapt to these variables begins to plateau after the initial acceleration to 75% body height. It may be that the necessary mechanical adaptations to increased drop height (for more beneficial landings) such as controlled lowering of the heel (Gross & Nelson, 1988) is difficult to achieve when drop height increases. The suggestion by McNitt-Gray (1991) that gymnasts land with reduced hip flexion (shown to increase vGRF (Blackburn & Padua, 2009)) from higher heights because of the demands enforced upon them during competition may be applicable to the current study's findings. The heights that the current study's traceurs performed their landings from may be similar to real world landing heights that they have experienced and formed ingrained behaviours towards. Further increases in drop height would be worthy of study to investigate this relationship further.

Results of comparisons between magnitudes present in precisions and rolls were found to be insignificant (p=0.1707 for mVF, p=0.3284 in LR p=0.5825 for TmVF) from a height of 75cm (Puddle & Maulder, 2010). It was for this reason that the current study was performed. In this study, the roll landings, although having lower magnitudes of mVF from all three body heights, illustrated faster TmVF and thus higher LR in the trials from 75% and 100% body height. It may be that the notion that forefoot landings reduce impact magnitudes while concurrently increasing impact loading due to the associated kinematics (Gittoes et al., 2009) is in fact true. It should be noted that the size of the force plate and the nature of the roll technique, means that vGRF could only be recorded for impact created by the feet during landing and not by the upper limbs or torso during the subsequent phases of the roll. This means that an unknown percentage of vGRF may be experienced by other parts of the body that the force plate cannot sample, thus showing reduced impacts for roll landings.

Observations by the researchers revealed that the individual roll landing techniques performed by the participants were not identical. Participants executed either A) a roll landing with a more vertical posture, collapsing into the roll, or B) a roll landing with a noticeable anterior lean and punched forward into the roll. This variation in technique can be explained by the pre-movement actions usually performed by traceurs when landing. As Parkour involves the use of movement at speed, a traceur will naturally jump forward from an obstacle and their landing will take the form of roll B. The restrictions imposed upon the traceurs in this study may have caused some to attempt to replicate their preferred style even without their forward momentum, while others adapted to the imposed restrictions. Without motion capture software integrated with the force plate (a limitation that could not be avoided), it is unclear which of these respective roll techniques was more beneficial or whether a certain technique was responsible for causing the mean results.

A similar punching action to that observed in the roll has been observed in other drop landing studies and their authors have made statements regarding the reasons and consequences of its use. Frederick et al., (2006) had skateboarders ollie down from a 45.7cm platform. Forefoot only landings were carried out by all participants to produce consistent force magnitudes between 4.5 and 5.0 BW. These results appear high compared to other studies dropping from similar heights but can be accounted for by the apparent “spiking” that the skateboarders perform. They purposely punch the ground upon contact to ensure adequate friction and stabilisation (Frederick et al., 2006). Gymnasts landed with higher ankle and hip extensor moments than recreational athletes (McNitt-Gray, 1993) suggesting a firmer or punched landing. McNitt-Gray (1993) hypothesised that this type of landing may enhance the ability of the gymnast to control their balance upon landing. These studies suggest that this response to landing is a likely response based around the demands put upon the tested athlete. Data in this study was presented as mean ± SD and did not allow for comparisons between individuals and so cannot highlight whether roll A produced less mVF, LR or slower TmVF. Future studies would benefit greatly from an integrated motion analysis system so that statements can be made on observed technique differences between participants. It may also be beneficial to investigate the mVF, LR and TmVF of both rolling techniques to provide a greater depth of information for technique instruction.

It was hypothesised in the current study that roll landings would produce lower mVF, LR and slower TmVF; this however was not entirely the case. Lower mVF was seen in roll landings at all heights, but roll landings had lower LR and slower TmVF at 50% body height only. Tant and Wilkerson (1988) made the statement that landing from a jump has received less interest than the takeoff [in the literature] in spite of there being a greater risk of injury as a consequence of improper impact absorption. While there has been much improvement in research investigating landing in recent years, this statement also applies to the amount of time traceurs actually spend practicing landing. The precision landing is certainly a more common landing manoeuvre utilised and practiced by traceurs. The higher interest and perhaps misplaced importance put on precision landings in Parkour training may account for the lower LR and slower TmVF present in precision trials at 75% and 100% body height. The magnitude of mVF (lower in roll landings) may be more difficult to attenuate in precision landings, but greater knowledge of the movement may allow traceurs to reduce the TmVF and therefore sustain lower LR upon impact.

The individual and therefore variable nature of Parkour makes it a great motivator for traceurs as training can occur at an intensity and pace of their choosing. However, this creates inconsistencies between traceurs and means that training years may not be an adequate predictor of landing experience. This insight may warrant the inclusion of traceurs (in future studies) who have participated in formalised Parkour classes where rolling is a frequently trained skill or perhaps an increase in the minimum years of training experience is required.

The magnitudes sustained by traceurs during precision and roll landings compare favourably to those found in the literature. The average body height from each drop height was 90.3cm (50%), 135.4 (75%) and 180.5 (100%). Studies utilising similar drop heights have found considerably higher vGRF than in the present study (Table 11).

Table 11. Comparison of vGRF between studies with similar drop heights

Author(s)	**Drop Height**	**Results (BW)**
(Present study, 2011)	90.3cm	3.2 ± 0.3 (Precision) 3.0 ± 0.4 (Roll)
	135.4cm	4.8 ± 0.8 (Precision) 4.7 ± 1.0 (Roll)
(Crowell et al., 1995)	107cm (4.57m/s)	8.9
	137cm (5.18m/s)	13.1
(Dufek & Bates, 1990)	100cm	2.2 ± 0.3 (F1) 5.1 ± 1.3 (F2)
(McNitt-Gray, 1991)	128cm	11.0 ± 2.3 (Gymnasts)
		9.1 ± 1.9 (Athletes)
(Whitting et al., 2007)	133cm (4.6m/s)	13.1 ± 2.6
(Zhang et al., 2000)	103cm	3.1 ± 0.3 (F1) 4.7 ± 1.0 (F2)
(Zhang et al., 2008)	90cm	5.2 ± 1.3 (F1) 7.8 ± 2.1 (F2)

Note: vGRF = vertical ground reaction forces, BW = body weight F1 = first peak, F2 = second peak.

No study reviewed as part of this research or any omitted from the literature review utilised a drop height of 180.5cm, yet traceurs were still able to land with 7.6 ± 1.5 and 7.0 ± 1.6 for precisions and rolls respectively, magnitudes lower than the majority of values presented above. Traceurs should be commended on their dedication to landing and safe practices as they are able to attenuate the forces from similar and sometimes greater drop heights. Based on this information it appears clear that other sporting codes and activities would benefit from utilising Parkour landings or participating in Parkour training to reduce vGRF on impact.

In 1996 it was estimated that over 7000 children under the age of 15 sustain injuries on playground each year, with the largest percentages of injuries occurring from falls (Chalmers et al., 1996). If Parkour landing techniques were taught to children, they might be substantial reductions in playground injuries. It is also likely that if these landings become innate behaviours, it would have positive change on the fall arrest capabilities of the individuals in later stages of maturation. For the same reasons as above, parachute landing fall instructors and researchers investigating landing in parachuting may be interested in the manner of landing used by traceurs. If Parkour landings (specifically the roll) were able to be utilised by paratroopers and recreational parachutists, reductions in landing injuries may be a possible outcome

Conclusion

Comparisons between Parkour roll and precision landings from varying height show that regardless of technique, increases in height result in significant increases in mVF and LR while TmVF decreases (though with diminishing significance between 75% - 100% body height).

Lower mVF present in roll landings implies that rolling is beneficial for traceurs to use over precision landings from any drop height. However, the importance placed upon LR and TmVF in the literature for reducing the chances of long term injury suggests that the lower magnitudes of LR and slower TmVF at 75% and 100% body height present in the precision may still make it a viable landing option. It is recommended that traceurs place even more importance on roll landing as the trends in the data of individual traceurs suggest that this technique is in fact the superior technique for force attenuation. There were however, two distinct roll landing techniques viewed by the researchers, but without motion analysis integration, no further investigation or statements could be made. In the current study this limitation was unavoidable, but would be of great benefit to future research in this area.

The comparisons made between landing magnitudes from the current study and those found in studies utilising practitioners from other sports (gymnastics, volleyball, basketball and parachuting, etc.) suggest that they would benefit from Parkour techniques or Parkour training. Similarly, children and adults alike may find great advantage in the practice of Parkour in order to reduce injury occurrence and severity.

The potential benefits of this research are many, but the removal of the current studies parameters from the real world setting that traceurs spend their time training in, limit the study's application. Traceurs should continue to use their landing techniques but devote further training towards perfecting the roll technique because of the trends found in individual participant's data. Future researchers are encouraged investigate this area of drop landing further, but with more elaborate apparatus allowing for a more natural test setting.

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Appendix A – Tables 8 and 9 with exact *p* values

Table 8. Differences in mechanical characteristics between heights for the precision task

	Comparison	Change in mean (%) with 90% confidence limit (lower ; upper limit)		Effect sizes	Qualitative inferences of effect sizes	*p* value
		Value	**Range**			
mVF (BW)	50% - 75%	45.3	36.6 ; 54.7	4.60	very large	0.0000003*
	50% - 100%	132.4	108.2 ; 159.3	10.36	very large	0.00000003*
	75% - 100%	59.9	39.6 ; 83.1	5.77	very large	0.0001*
TmVF (s)	50% - 75%	-54.3	-62.4 ; -44.4	-1.11	small	0.00002*
	50% - 100%	-61.3	-69.7 ; -50.6	-1.35	moderate	0.00002*
	75% - 100%	-15.4	-31.0 ; 3.8	-0.24	small	0.1694
LR (BW/s)	50% - 75%	34.6	177.7 ; 303.1	1.40	moderate	0.00000002*
	50% - 100%	446.2	320.9 ; 608.9	1.97	moderate	0.00000002*
	75% - 100%	63.3	25.8 ; 111.8	0.57	small	0.0061*

Note: mVF = maximum vertical ground reaction force, BW = bodyweight, TmVF = time to maximum vertical ground reaction force, s = seconds, * = significant difference ($p<0.05$).

Table 9. Differences in mechanical characteristics between heights for the roll task

	Comparison	Change in mean (%) with 90% confidence limit (lower ; upper limit)		Effect sizes	Qualitative inferences of effect sizes	*p* value
		Value	**Range**			
mVF (BW)	50% - 75%	53.6	44.1 ; 63.7	3.19	very large	0.00000001*
	50% - 100%	130.7	112.4 ; 150.5	6.22	very large	0.0000000001*
	75% - 100%	50.2	40.1 ; 61.0	3.03	very large	0.00000004*
TmVF (s)	50% - 75%	-70.5	-79.0 ; -58.7	-3.11	very large	0.00004*
	50% - 100%	-76.5	-82.1 ; 69.1	-3.69	very large	0.000002*
	75% - 100%	-14.6	-42.6 ; 28.0	-0.39	small	0.5028
LR (BW/s)	50% - 75%	358.6	253 ; 495.6	3.43	very large	0.00000005*
	50% - 100%	709.5	491.2 ; 1008.3	4.71	very large	0.00000003*
	75% - 100%	67	15.0 ; 141.5	1.16	small	0.0303*

Note: mVF = maximum vertical ground reaction force, BW = bodyweight, TmVF = time to maximum vertical ground reaction force, s = seconds, * = significant difference (p<0.05).