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KINEMATICS AND KINETICS OF THE TAEKWON-DO TURNING KICK

JAKE N. PEARSON

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Abstract

Taekwon-Do is a martial art famous for its powerful kicking techniques, and the turning kick is the most frequently used of these techniques. The purposes of the present experiment were a) to describe the kinematics of Taekwon-Do turning kicks, and b) to determine those kinematic variables that were most closely related to large impact forces in turning kicks. A deterministic model was developed to identify all of the mechanical factors that determine average impact force over the duration of impact. The impulse, duration of impact, and three-dimensional kinematics, as identified by the model, were recorded for maximal turning kicks performed by fifteen skilled male subjects. Only their best kick was selected for analysis. Mean impact force was 292±54 N, and mean linear velocity of the toe immediately before impact was 13.4±1.6 m/s. The summation of speed principle was found to be relevant to the Taekwon-Do turning kick. Significant positive Pearson Product Moment correlations with impact force were found for: impulse, body mass, linear speed of the toe and ankle immediately before impact, change in angular speed at the knee over Phase 2, and length of the thigh. Generating high linear speeds of the foot appeared to be the surest way of producing large impact forces. Based on these results, foot speed drills and exercises involving coordination between the thigh and shank were recommended as effective ways for practitioners to improve the impact force of Taekwon-Do turning kicks.

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Chapter 1

Introduction

Taekwon-Do is a dynamic form of unarmed self defence that utilises the entire body, and can be distinguished from other martial arts by its focus on kicking techniques. Snap kicks, a classification of Taekwon-Do kicks, can be performed quickly and possess the force to break the bones of an opponent. Two such kicks are the turning kick (known as roundhouse kick in other martial arts) and the front kick. In an apparent contradiction, the turning kick is the most frequently used in Taekwon-Do competition (Lee, 1983), yet the front kick has been the subject of the majority of biomechanical research (Ahn, 1985; Hwang, 1987; Park, 1989; Beraud & Gahery, 1995; Sorenson, 1996). The front kick has been described as displaying the proximo-distal pattern characteristic of fast unloaded movements where the goal is maximum linear velocity of the distal endpoint (Sorenson, 1996). The turning kick, although employing additional body rotations, also appears to employ a similar pattern to produce great velocity and impact force. The kicking leg travels in an arc towards the front with the knee in a chambered position. The knee then extends and the target is struck with the ball of the foot near full extension. The contribution of the proximo-distal pattern and other kinematic parameters to the resultant force of the turning kick has yet to be scientifically investigated.

Purpose

The purposes of the present study were a) to describe the kinematics of Taekwon-Do turning kicks, and b) to determine those kinematic variables that were most closely related to large impact forces in turning kicks.

Significance

The need for the present study focused around three main issues. Firstly, determining the kinematic factors that are contribute to a forceful kick is fundamental to the improvement of the techniques of Taekwon-Do and other martial arts. Secondly, there has been very little scientific research conducted on the Taekwon-Do turning kick. Finally, knowing which factors are important in developing an effective turning kick enables practitioners and instructors to focus their training on developing these components.

The original purpose of martial arts was to protect oneself against attackers. Consequently, an emphasis was placed on developing techniques that would disable an opponent. While self-defence is still important in modern society, the tournaments have become a popular way to test one's techniques. Maximising the impact force of kicks is beneficial to all of the three main areas of Taekwon-Do competition: sparring (free-fighting), patterns (forms), and destructions (breaking of wood and tiles). Together with psychological and physiological factors, the biomechanics of movement is an essential component in determining the impact force of a kick. Choi (1988) states that Taekwon-Do techniques are based on the laws of physics, and proposes the "theory of power" as a basis for ideal technique. For example, a Taekwon-Do instructor often tells students to drive their hips forward more vigorously at the beginning of the kick. Martial arts theories tend to be heavily rooted in tradition, and as such have not been biomechanically analysed to the same degree as more modern sports such as swimming, gymnastics, and cycling (Pieter, 1994). Technology and associated science is now assuming a more important role in helping athletes gain the competitive edge. As Taekwon-Do raises its profile, demonstrated by its recent inclusion as a full Olympic event, it must be prepared to become the subject of scientific study.

The Taekwon-Do turning kick has received very little attention in the scientific literature to date, although it is the most frequently used kick in training and competition. Lee (1983) found that almost 60% of techniques used in a Taekwon-Do championship were turning kicks. Previous biomechanical studies focused upon calculating the peak velocity of turning kicks by elite performers (Pieter & Pieter, 1995; Serina & Lieu, 1991). Pieter and Pieter (1995) used timing lights to record velocity, and also measured impact force of the turning kicks. Serina & Lieu (1991) took video recordings from the top and side which were fitted into two-dimensional linkage models to analyse the injury potential of the turning kick along with three other kicks. One of the main reasons for the lack of research on the turning kick appears due to its rotational nature, making three-dimensional analysis essential. The majority of videography studies have looked at the front kick using a two-dimensional analysis (Ahn, 1985; Hwang, 1987; Park, 1989; Sorenson, 1996), due to the front kick being essentially a planar movement that involves minimal body rotation. Considering that the majority of Taekwon-Do kicks involve body rotation of some kind, and with the recent advances in technology, the logical progression appears to be to three-dimensional analyses. A study incorporating three-dimensional videography can investigate the turning kick, confirm whether this proximo-distal pattern is evident, and assess the association of this sequencing to the resultant impact force.

Once the critical factors most closely related to the impact force of a turning kick are known, then training can be focused on developing these components. Specifically, those factors that are under the performer's control, once identified, can be emphasised during training. Depending on the kinematic variable that is identified, certain training strategies can be adopted. For example, if the angular velocity at the knee towards the end of the kicking motion was found to be critical, then the athlete could begin specific resistance or plyometric training to improve this particular aspect. As well as training programs, technique modifications may also be demonstrated to be beneficial in increasing the impact force of kicks. Once objective measures are identified, comparisons can be made with elite athletes.

Hypotheses

1. At least one of the kinematic variables measured will be found to significantly correlate to impact force.
2. The summation of speed principle will be supported for the turning kick.

Delimitations

A number of delimitations have been imposed by the investigator in order to test the research hypothesis:

1. The subjects for this study were 15 males who had been training in ITF style Taekwon-Do for at least 2 years, and were available to be tested at the specified time.
2. Subjects were assigned to come in for a one hour testing session at some point over a period of 2 days at the School of Physical Education Biomechanics Laboratory, University of Otago.
3. The analysis was delimited to the Taekwon-Do turning kick performed with the right leg, irrespective of the subject's dominant side.

4. A water filled bag with a marked area at the subject's solar plexus height and at a distance of the subject's choice will be the target for the turning kick.

5. Subjects were asked to perform a maximal effort turning kick, with the constraints that kick the impacted within the specified target area, and they began and finished the movement in a stationery position with both feet completely on the force platform.

6. A force platform (Advanced Mechanical Technology Inc., Newton, MA) sampling at 1000 Hz was used to calculate impulse, and a high speed camera (Motion Analysis Corp., Santa Rosa, CA) sampling at 200 Hz was chosen to obtain the impact duration of the kicks.

7. Kinematic data was acquired using videography collected at 50 Hz and analysed using the Peak Motus system (Peak Performance Technologies, Englewood, CO).

Limitations

The following limitations are also acknowledged:

1. Only the turning kick that each subject selected as their best was analysed.

2. Subjects were given 15 minutes to complete a warm-up that they deemed to physically and mentally prepare them to perform full-power kicks.

3. There was no control over whether or not the perceived maximal effort by subjects corresponded with the greatest impact force that they were capable of.

4. It was considered that factors such as the day of the week, time of day, and the performer's physical condition did not affect subjects' performance.

5. The distance of the bag from the subject was left up to himself to choose, and the height of the target area was positioned at the same level as his abdomen.

6. It was deemed that the subjects were completely stationery at the beginning and end of the kicking motion.

7. Each body segment was modelled as a rigid link.

8. The properties of the punching bag were taken to be constant for all of the kicks that contacted within the marked target area.

9. The mass of the foot was taken to be proportional to the mass of the whole body.

10. Verbal encouragement was considered to be equally motivating for all subjects.

Chapter 2

Review of Literature

Introduction

The literature relevant to the present study will be covered under four main sections. The first presents an overview of three-dimensional videography, specifically the Direct Linear Transformation (DLT) method. The second section explains the general theories behind the development of so-called deterministic models usually used for qualitative analysis. The third section summarises some studies on general kicking that are relevant to the present study. The forth section focuses on research on martial arts kicks, and is divided into three sub-sections: kinematic analyses of martial arts kicks, research on the ground reaction forces during kicks, and studies investigating the impact force of techniques. The final section is a summary of the main points from the chapter.

Three-dimensional Videography using DLT method

Up until the last 25 years or so, motion analyses using video recordings were limited to movements carried out in just one plane, which involved a two-dimensional analysis. It became increasingly apparent that most complex human movements involve motion in more than one plane, leading to the development of three-dimensional video analysis techniques (Shapiro, 1978). The most widely applied has been that developed by Abdel-Aziz and Karara (1971). Their method, which required two or more cameras, involved the DLT from image coordinates into object space coordinates. This establishes a relationship between digitised coordinates from the two camera views and the corresponding coordinates in three-dimensional space.

The DLT algorithm can be reduced to a set of two equations, expressed as:

$$u + \Delta u = \frac{L_1 X + L_2 Y + L_3 Z + L_4}{L_9 X + L_{10} Y + L_{11} Z + 1}, \text{ and}$$

$$v + \Delta v = \frac{L_5 X + L_6 Y + L_7 Z + L_8}{L_9 X + L_{10} Y + L_{11} Z + 1},$$

where u and v are the image coordinates and Δu and Δv are the image coordinate correction for lens distortion. The object point coordinates are X, Y, and Z, and the constants L_1 to L_{11} are the DLT parameters. The DLT parameters define calibration, position, and orientation of each camera.

In order to determine the DLT parameters, a calibration frame with non coplanar points of known coordinates relative to an arbitrary reference frame is filmed first. Each calibration point provides two equations, and, as the DLT algorithm requires a minimum of eleven parameters to be solved, a minimum of six calibration points are required. Once the DLT parameters have been determined, the position of any marker within the object space can be obtained. This is accomplished by transforming the image coordinates from each camera into the global coordinates relative to the arbitrary reference frame mentioned earlier. However, if the cameras are altered in any way, the calibration process must be redone.

The DLT method is suitable and convenient for a number of reasons. Firstly, only two nonmetric (where the internal camera parameters are not previously known) cameras are required, which reduces the initial capital expense and digitising time during analysis. Secondly, the orientation of the image reference frame with respect to the object reference frame, and the distance from the camera to the object do not need to be known. Thirdly, this technique is extremely flexible in that the cameras are able to be positioned almost anywhere, as long as the object of interest is in the field of view of both cameras. Finally, the ability of the DLT method to locate points in space has been shown to meet the accuracy requirements associated with human movements (Shapiro, 1978). An investigation of the accuracy of the DLT reconstruction found errors up to 6-7 mm for the resultant three-dimensional coordinates within the calibration space (Chen, et al., 1994). However, when points outside the calibration space are analysed, the error increases significantly (Wood & Marshall, 1986).

Development of a Deterministic Model

Although this study is primarily of a quantitative nature, it will include a technique from qualitative analysis: deterministic modelling. Hay & Reid (1982) outline the four steps of a qualitative analysis as follows:

1. Development of a deterministic model showing relationships between the result and factors which produce that result.
2. Observation of the performance and identification of faults.
3. Evaluation of the relative performance of these faults.
4. Instruction of the performer based on the conclusions.

Only step one, development of a deterministic model, will be discussed here. A deterministic model divides a skill or movement into the mechanical factors that completely determine the outcome or result of that skill. Each factor can be independently identified, and the interrelationships between factors in the model become clear. The contribution of a given factor can be assessed partly by its position in the model, but validation by scientific investigation is necessary to be certain. Consequently, an important application of deterministic modelling is its use in identifying all of mechanical factors important in the success or outcome of a specific skill without unnecessary duplication. It follows that those factors identified are, where possible, what an investigator should measure.

Deterministic models have a result at the apex that can be either objective or subjective, depending on how it is measured. The result is the goal or outcome of the skill or activity that is modelled. Examples of objective measures are the distance a javelin is thrown, the weight lifted, or the height jumped. Subjective measures are used for situations where a score is awarded by judges, or advantage is gained from a pass. Where necessary, the next step in developing a qualitative model is the division of the result. This step is only applicable where the result can be seen to consist of distinct parts. The final step is to break the result (or divisions of the result) down into factors that completely determine it. These factors in turn can also be divided down into determining factors until further division is redundant, or all the factors of interest have been included.

When the model is being developed, it is imperative that the following conditions are fulfilled: a) each factor at each level is a mechanical quantity, and b) when a factor is divided into sub-factors, it must be completely determined by these sub-factors. Such a model is referred to by Watkins (1987a) as a mechanical approach, as opposed to a sequential approach, to qualitative analysis. In a later article on quantitative movement analysis, Watkins (1987b) suggests that the two objectives of such study are to a) evaluate the end result of a movement, and b) examine and/or evaluate the sequence of movements or movement pattern responsible for the end result. It is important to note that a given result can have many different models, depending on the subsequent analysis approach used; the model that is best for a situation depends on the type of analysis that will follow.

Hay & Yu (1995) used a deterministic modelling approach to determine the critical characteristics of technique in throwing the discus. A theoretical model of mechanical factors of the athlete's technique that completely determined the distance of the throw was developed in order to identify the measurement variables. Elite subjects were videoed and the three-dimensional kinematic variables identified in the model were measured over selected phases. Finally, correlations with the distance thrown were computed, and conclusions drawn from these results.

General Kicking Literature

Kicking research has tended to focus on ball kicking and the sequence of segmental rotations associated with achieving a high foot velocity at impact. It has been observed that during the initial phase of a kicking motion, thigh rotation appears to dominate the activity, whereas throughout the later stages thigh rotation decreases considerably while that of the shank increases (Roberts, et al., 1974; Putnam, 1983). Putnam (1993) describes the "summation of speed" principle, where each distal segment starts its motion at the instant of greatest speed of the preceding proximal segment, and reaches a maximum speed greater than that if its predecessor. Philips (1985) found greater consistencies in the movement pattern of maximal kicking trials for an elite compared to a club player. This reflected a highly sophisticated and precisely timed neuromuscular pattern, for a sequenced movement.

Research looking at the ground reaction forces (GRFs) during kicking has tended to concentrate on the dynamic loading of the support leg during the football punt and soccer kick (Roberts, et al., 1974; Kermond & Konz, 1978; Asami & Nolte, 1983). One study (Kermond & Konz, 1978) found that the integral of the somersault torque against time curve significantly correlated with the distance of the kick. Generally however, from these studies it is unclear what the effect of different magnitudes or patterns of GRFs on performance is.

Martial Arts Kicks

Firstly, a review will be given of studies that have investigated the kinematics of martial arts kicks. Secondly, those studies that have measured the GRFs during martial arts kicks are presented. Lastly, consistencies and variations in previous studies that have measured the impact force of martial arts techniques will be discussed.

Kinematic Analyses of Martial Arts Kicks

High speed video analysis has been the most widely used method of study to date, and given precise data collection and analysis, appears to be a reliable and valid method for kinematic and kinetic analyses. Published research in this area began with basic cinematographic analyses and models of the physics of Karate techniques (Blum, 1977; Feld, et al., 1979). Since that time, the majority of biomechanical studies on the martial arts have looked at the front kick using a two-dimensional video analysis (Ahn, 1985; Hwang, 1987; Park, 1989; Beraud & Gahery, 1995; Sorenson, 1996). The pattern of the kinematics of the kicking leg during the execution of a front kick has been described, and peak linear velocities of the foot have been observed within the range of 12-14 m/s. The proximo-distal pattern of the kinematics of the front kick led to an investigation into the interactions between the segments of the kicking leg (Sorenson, 1996). Serina & Lieu (1991) took high speed video recordings from the top and side to analyse the injury potential of the roundhouse[1] and other kicks. The period

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[1] A roundhouse kick is the same as the turning kick, except that the target is

immediately before impact was analysed, and peak linear velocity of the foot was about 16 m/s for the roundhouse kick. The video data was fitted into two-dimensional linkage models, hence this study was not strictly a three-dimensional analysis.

Three-dimensional videography was used by Sidthilaw (1997) to investigate the kinematics of the Thai boxing roundhouse kick, which is somewhat similar to the Taekwon-Do turning kick. Data was collected for the linear velocity of the ankle and knee, and angular velocity at the knee and hip of the kicking leg up until impact. The peak angular velocity at the hip preceded the peak angular velocity at the knee for every subject. The linear velocity of the foot immediately before impact during the execution of the round kick has also been measured by electronic timing lights (Conkel et al, 1988; Pieter & Pieter, 1995). These studies tested elite athletes, and found final linear velocities of 14 - 16 m/s. Previous research on the turning kick has focused on the period immediately before impact, and on the preceding movement pattern. Sorenson (1996, pp. 494) states that, "in order to assess the contribution of different joint angular of linear velocities to the outcome (final velocity) of a certain movement, it is necessary to study the time course of the entire movement". This has not been done by researchers previously, possibly due to the extra work involved in digitising and analysis.

Ground Reaction Forces during Martial Arts Kicking

There is has been very little research conducted that investigates the GRFs during martial arts kicking, despite this being an intuitively important determinant of performance. Beraud & Gahery (1995) measured the GRFs of both legs during performance of a low front kick against a bag used in French

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struck with instep or shin instead of the ball of the foot.

boxing. There was little difference in the push off force when the kick changed from "touch" to "strike" mode. One study investigated the vertical GRFs of the support leg during the performance of different types of Taekwon-Do front kicks (Park, 1989). No significant differences between the kicks were found, but maximum vertical forces of about 1.4 times body weight were reported.

Measurement of the Impact Force of Martial Arts Techniques

Force seems to be a much more elusive variable than speed; it is far more dependent on the methods used to determine it (Pieter, 1994). Pieter & Pieter (1995) measured the force of the side kick, round kick, spinning back kick, and reverse punch against a water-filled bag with a built-in force sensor unit. For the round kick, forces up to 620 N were recorded, and force was found to correlate with body mass and the peak velocity of the kick. Conkel, et al. (1988) used piezoelectric film, similar to that used to measure pressure distribution on the foot during gait, and attached it to a heavy bag to measure the impact force of front, side, back and roundhouse kicks. Impact forces of up to 470 N were recorded for the roundhouse kicks. In contrast, Sidthilaw (1997) recorded peak forces of up to 14000 N for Thai boxing roundhouse kicks. Peak force was measured using three accelerometers mounted inside a bowling ball which was placed inside a padded kicking bag. Body mass and linear velocity of the ankle were found to positively correlate with peak force and impulse of the kick. Shibayama & Fukashiro (1997) measured the impulses of Karate punches using a vertically mounted force plate covered with a hard cushion. They recorded impulses of between 9 and 18 N.s.

Studies that have evaluated the injury potential of kicks can also be classed as investigating their impact force. Schwartz, et al. (1986) attached a triaxial accelerometer to a model of a human head to assess the force of full-contact Karate techniques. Peak accelerations of the model head of up to 120 G were recorded which corresponded to that experienced during automobile collisions. The injury potential to the mid-section, or thorax, has been quantified for the roundhouse, spinning roundhouse, side and back kicks (Serina & Lieu, 1991). Peak velocity and energy content were two separate criteria for injury potential, and all kicks were concluded to possess the ability to cause damage. Roundhouse and spinning roundhouse kicks had higher peak velocities, whereas side and back kicks had greater leg energy content.

It is difficult to find consistencies in research on the impact force of martial arts kicks due to the range of definitions and methods used. Authors have often neglected to clarify whether they were measuring peak, average, or some other form of "impact force". It seems that the term "force" is not always used in the strict scientific sense. Comparisons are further confounded by differences in the targets that subjects strike. The size and elasticity of the target would have an effect on the impact force reading obtained. Finally, the instrumentation that records has an influence on the value of impact force that is acquired, and thus must be valid and reliable. Video data, accelerometers, piezoelectric film, and changes in pressure are all indirect measures of the impact force, hence a force platform seems the best form of instrumentation to collect such data. Despite variations in data collection techniques it is generally evident that the roundhouse kick performed by elite athletes can generate large impact forces that possess the potential for serious injury to an opponent.

Summary

The DLT method was summarised, and demonstrated by previous research to be a valid and reliable method of three-dimensional reconstruction. The steps in developing a deterministic model were outlined, and shown to be useful for selecting measurement variables for a quantitative analysis. The summation of speed principle was introduced as a mechanism for explaining the large foot speeds generated during kicking. Finally, previous relevant literature on the topics of kicking and martial arts was reviewed. A series of analyses have provided consistent patterns and magnitudes of the kinematics of the front kick, but a lack of research on the complete movement pattern of the turning kick was identified. The influence of GRFs on kicking performance has not been determined. Despite doubts concerning the validity of previous impact force definitions and measurements, the turning kick has been seen to generate high impact forces that generally correlate positively with body mass and peak linear velocity of the kicking foot.

Chapter 3

Methodology

Definitions

The Linkage System

In order to biomechanically analyse human movements, the body of interest is often represented as a simplified mechanical model (Andrews, 1995, pp. 145). This model should represent the body as accurately as possible, within the constraints imposed by the experimenter. The system of interest in the present study was the lower extremity that was used to perform a turning kick against a stationery bag. For the purpose of this analysis, the system of the right leg was modelled as three rigid, linked segments, as shown in Figure 1.

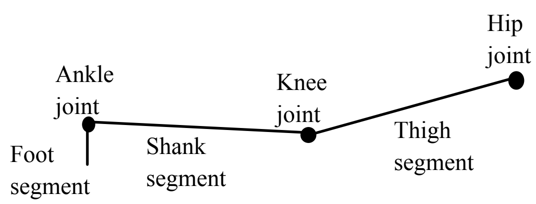


Figure 1. Overhead view of the kicking leg showing joints and segments of interest.

The most distal segment, or foot, was defined as the straight line from the third metatarso-phalangeal joint to the center of rotation (COR) of the ankle joint. The ankle joint COR was represented by the midpoint of the line connecting the medial and lateral malleoli. The ankle joint was modelled as a hinge joint with one rotational degree of freedom (DOF), and the angle at the ankle joint was defined as the internal angle between the foot and the shank.

The middle segment, or shank, was defined as the straight line connecting the ankle joint COR and the knee joint COR. The knee joint was modelled as a hinge joint with one rotational DOF, with the COR lying at the midpoint of the line between the medial and lateral epicondyles. The angle at the knee joint was defined as the internal angle between the shank and the thigh.

The most proximal segment in the system, or thigh, was defined as the straight line connecting the knee joint COR and the hip joint COR. The hip joint was modelled as a ball and socket joint with three rotational DOF, and the COR of the right hip joint was represented by the point lying one quarter of the distance along the line connecting the right greater trochanter to the left greater trochanter. Due to the more complicated three-dimensional nature of the hip joint, the angle was divided into two components that were most convenient for the analysis. One component of hip angle was the included angle that the thigh segment made with the horizontal plane, which will be referred to as the elevation angle. The second component of hip angle was the angle that the projection of the thigh onto the horizontal plane made with the Y axis (see section below defining the reference frame), which will be referred to as the horizontal rotation angle.

Free Body Diagram

A free body diagram (Figure 2) shows an overhead view of all the external forces acting on the system when the foot is making impact with the bag. At impact, a force is made on the system at the toe by the bag (F_b) which is equal and opposite to the force made by the foot on the bag. A force is also exerted on the system by the rest of the person's body via the hip (F_h).

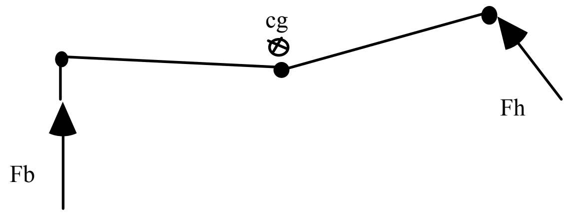


Figure 2. Free body diagram of the kicking leg.

Reference Frame

All kinematic variables and external forces acting on the system are expressed with respect to a right-handed inertial reference frame (referred to as global reference frame), represented diagrammatically in Figure 3.

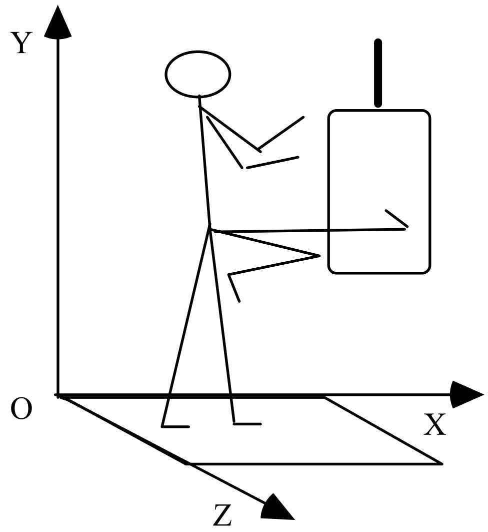


Figure 3. Diagram of the origin and reference axes relative to the testing set-up.

The origin, marked O, corresponds to the far corner of the force platform. The positive X direction follows the edge of the force platform towards the bag, the positive Y direction is vertical from the floor, and the positive Z direction follows the other edge of the force platform from left to right when facing the bag.

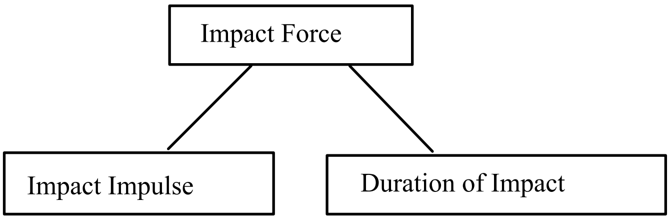
Phases and Critical Instants

For the purpose of analysis, the turning kick movement has been divided into three components: the kick, the impact, and the recovery. The start of the kick was defined as the instant that the heel of the kicking leg first leaves the ground, and the finish of the kick defined as the instant immediately before the foot makes contact with the target. This period has been further divided into two phases: 1) start of the kick until the point of maximum knee flexion of the kicking leg, and 2) the point of maximum knee flexion until the finish. The beginning of impact was when the bag surface was first deformed by the foot, and the end of impact was the first instant that the foot no longer in contact with the bag. The recovery was from the end of impact until the foot returns back to the floor.

Deterministic Model

In order to determine the important factors that contribute to the impact force of a turning kick, a "deterministic model" (Hay & Reid, 1982) was developed. For the purpose of the present study, impact force is taken as a measure of the average impact force by the foot on the bag over the period of contact. Average impact force (F) of the turning kick can be completely determined by a) the resultant linear impulse made by the foot on the bag (impact impulse), and b) the duration of impact (t). This is based on the equation, impact impulse = Ft, which can be rearranged to give:

$$F = \text{impact impulse} / t$$



Because this is a situation involving a collision between two bodies, Newton's "law of impact" must be considered. This states that over the course of an impact between two bodies, there is a constant relationship between the differences in velocities immediately before and immediately after impact (Hay, 1993). This constant is called the coefficient of restitution (e), and is a measure of the elasticity between the two bodies involved in the impact. The elasticity determines the degree to which the velocity of the bodies immediately after separation differs from the velocity immediately before impact. This can be calculated by the formula:

$$-e = (v_f^a - v_b^a) / (v_f^b - v_b^b) \qquad (1)$$

where v_f^b and v_f^a are the velocities before and after impact of the foot, and v_b^b and v_b^a are the velocities before and after impact of the bag respectively.

According to the principle of conservation of linear momentum, if no external forces acted upon the foot+bag system, then the total linear momentum would remain constant over the whole impact. However, the bag is attached to the ceiling, and the foot is connected to the rest of the lower leg and body. These external sources therefore exert forces on the foot+bag system during the impact, changing the total linear momentum. In other words, "the application of an impulse will result in a change in momentum of a system". This is called the "impulse-momentum relationship" (Enoka, 1988, pp. 77). Consequently, the total linear momentum of the foot+bag system is:

$$m_f v_f^a + m_b v_b^a = m_f v_f^b + m_b v_b^b + \text{external impulse} \qquad (2)$$

where $m_f v_f^b$ and $m_f v_f^a$ are the linear momenta of the foot before and after impact respectively, $m_b v_b^b$ and $m_b v_b^a$ are those of the bag, and external impulse is the impulse exerted on the system by the ceiling attachment and the rest of the performer's body via the hip.

Equations (1) and (2) can be rearranged to make v_b^a the subject, as demonstrated by equations (3) and (4) respectively. These are then combined as shown by equation (5), and manipulated to solve for v_b^a and v_f^a.

$$v_b^a = e(v_f b - v_b^b) + v_f^a \qquad (3)$$

$$v_b^a = (m_f v_f^b + m_b v_b^b - m_f v_f^a + \text{external impulse}) / m_b \qquad (4)$$

$$e(v_f b - v_b^b) + v_f^a = (m_f v_f^b + m_b v_b^b - m_f v_f^a + \text{ext imp}) / m_b \qquad (5)$$

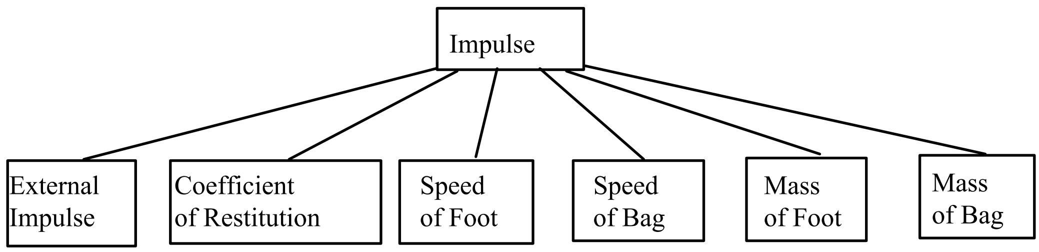
The impulse of interest in the model and present study is the linear impulse made by the foot on the bag. This can be determined using the impulse-momentum relationship on the bag system. The total linear momentum of the bag system after impact is $m_b v_b^a = m_b v_b^b$ + impact impulse. From this point on, "impulse" will refer to "impact impulse" unless stated otherwise. The equation can be rearranged to give:

$$\text{impulse} = m_b v_b^a - m_b v_b^b \qquad (6)$$

Because v_b^a (and v_f^a) can be replaced by m_b, m_f, v_b^b, v_f^b, e, and 'external impulse', based on equations (4) and (5), the linear impulse made by the foot on the bag can determined as a function of these terms.

$$\text{impulse} = f\,(m_b, m_f, v_b{}^b, v_f{}^b, e, \text{external impulse}) \qquad (7)$$

The impact between the foot and the bag will be assumed to be a "direct impact". This implies that prior to impact the foot is moving a line at right angles to the surface of the bag (Hay, 1993). Therefore, only the component of velocity perpendicular to and travelling towards the bag surface is of interest, so the scalar term "speed" can replace "velocity" in the present experiment. The two speeds referred to in the model below are those at the instant immediately before impact.



The external impulse will be presumed to be zero for the present experiment. Because the bag is free to swing about its attachment, and the duration of impact is very short (typically around 100 ms), the impulse exerted by this source can be considered negligible. The mass, speed immediately before impact, and coefficient of restitution of the bag were assumed to be constant throughout the experiment, so will also be excluded from further analysis. The mass of the foot will be represented by the body mass, as it is assumed that these are proportionally equal for all subjects.

The variable that is under the performer's control when performing a turning kick is the speed of the foot immediately before impact. Linear speed can de determined from angular speed (ω) and the radius of rotation (r), or

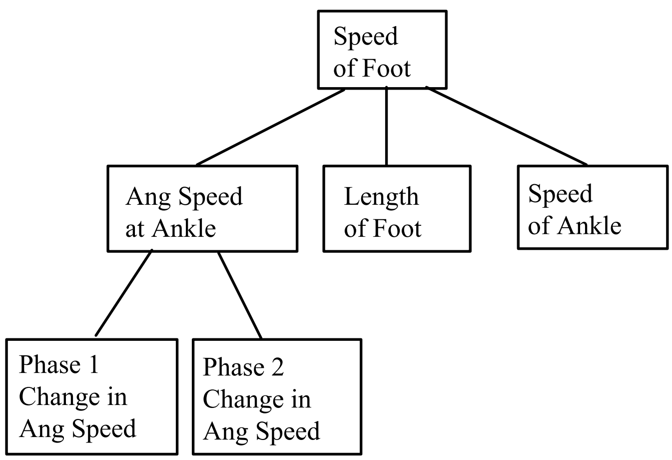
$v = \omega r$. Consequently, the speed of the endpoint of the foot (v_t) can be calculated by adding the linear speed of the center of the ankle joint (v_a) to the product of the angular speed at the ankle (ω_a) and the length of the foot (l_f), or:

$$v_t = v_a + \omega_a l_f \tag{8}$$

The angular speed at the ankle joint is defined as the rate of change of the angle at the ankle joint at the instant immediately before impact. The linear speed of the center of the ankle joint (and all the joints that follow) is measured with respect to the global reference frame, defined earlier in this chapter.

Because the motion begins from rest, the angular speed at the ankle joint immediately before impact is comprised of the change in angular speed from the start to the finish of the kick (see section on phases and critical instants earlier in this chapter). Therefore, the final angular speed at the ankle is the sum of the change in angular speed during the first phase (ω_{a1}) and the change during the second phase(ω_{a2}). The changes in angular speeds are computed by subtracting the instantaneous speed at the start of the phase from that at the end.

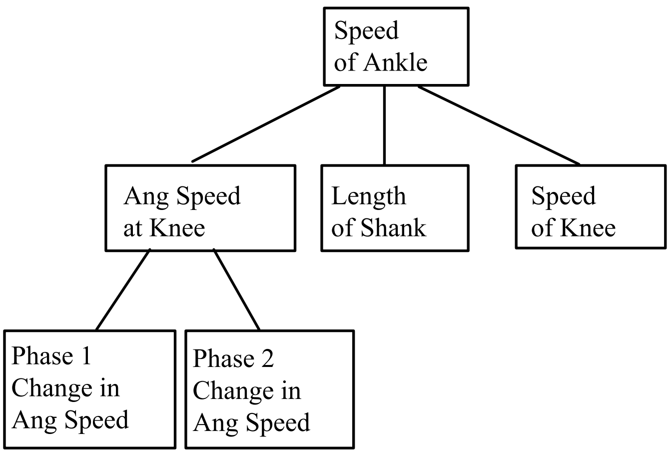
$$\omega_a = \Delta\omega_{a1} + \Delta\omega_{a2} \tag{9}$$



The speed of the ankle joint center immediately before impact is the sum of the linear speed of the center of the knee joint at that instant (v_k) and the product of the angular speed at the knee (ω_k) and the length of the shank (l_s), or:

$$v_a = v_k + \omega_k l_s \tag{10}$$

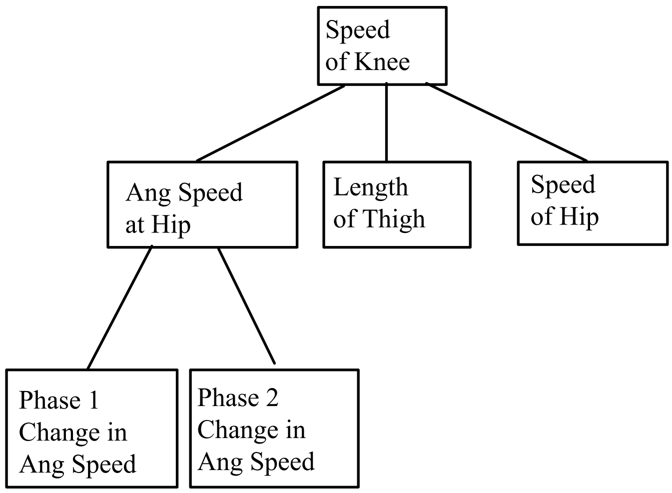
The angular speed at the knee is the rate of change of the angle at the knee joint immediately before impact. The angular speed at the knee joint is the sum of the changes over the two phases.



Finally, the linear speed of the knee joint center is the sum of the linear speed of the center of the hip joint (v_h) and the product of the angular speed at the hip (ω_h) and the length of the thigh (l_t), or:

$$v_k = v_h + \omega_h l_t \tag{11}$$

The angular speed at the hip is the rate of change of the angle at the hip joint immediately before impact, and is also summed over the two phases.



The complete deterministic model for the impact force produced by a turning kick is presented below in Figure 4.

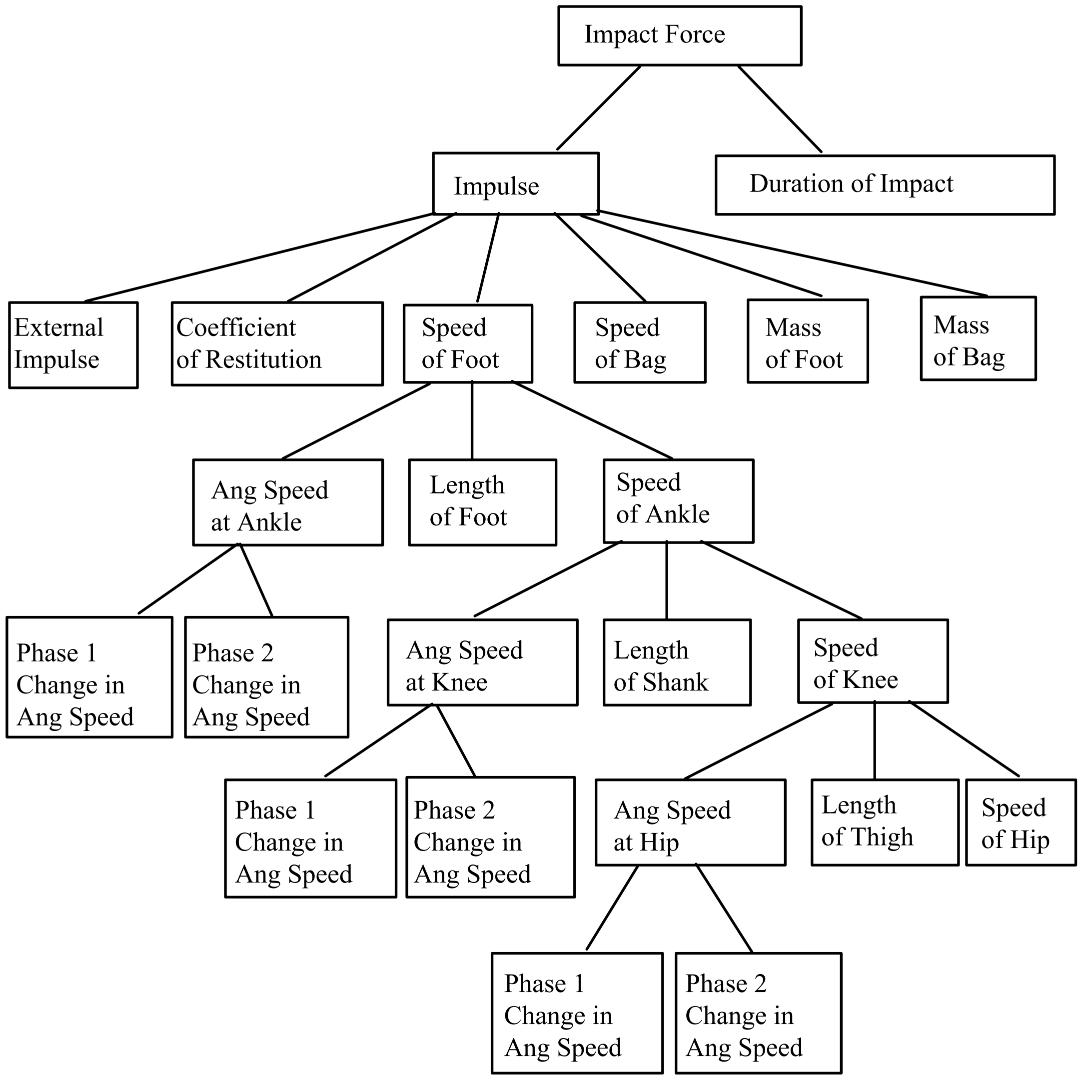


Figure 4. Deterministic model for the impact force exerted by a turning kick.

The deterministic model described above identifies the mechanical factors that completely determine the impact force of a turning kick. The degree to which each of these kinematic variables is related to the magnitude of impact force was assessed by determining their respective correlation coefficients.

Subjects

The subjects for this study were 15 skilled adult male Taekwon-Do practitioners recruited from two local clubs in the city of Dunedin. "Skilled" is defined as having been actively training in Taekwon-Do for at least 2 years. All subjects volunteered, and were given an information sheet on the experiment. They had sufficient opportunity to ask questions, then signed an informed consent form. Copies of the information sheet and consent form are given in Appendices A and B respectively.

Apparatus and Procedure

Data Collection

Subjects' height was measured by a vertical ruler, body mass was measured using calibrated digital scales, and segment lengths were measured with a tape measure between the anatomical landmarks outlined in the description of the linkage model earlier in the chapter. Means and standard deviations of the anthropometric and training experience data collected are given in Appendix C. The deterministic model established the kinetic and kinematic variables to be measured. Impulse was acquired using a force platform, duration of impact calculated by high speed video, and the remaining kinematic data obtained by 3D videography using the DLT algorithm. Each of the fifteen subjects performed five maximal effort turning kicks on a stationery bag, and data were collected for every kick.

Force platform.

The current experiment used an AMTI force platform (model LG6-2-1, Advanced Mechanical Technology Inc., MA) to simultaneously record ground reaction forces along the three orthogonal axes shown in Figure 2. The signal was amplified by an AMTI strain gauge amplifier (model SGA6-4) with bridge excitation set at 10V and gain set at 2000. The bridge balancing was set so that each channel was adjusted to zero before each testing session.

The signals from the three channels were displayed and recorded by the Chart program of MacLab (ADInstruments, NSW, Australia) running through a Power Macintosh. In the A/D conversion each channel was sampled at 1000 Hz with a range of 5V and the reading in Volts was converted to Newtons according to the calibration matrix set by the manufacturer, the bridge excitation, and the gain. The calibration accuracy was tested by checking that forces applied to the force platform corresponded to the forces recorded by the equipment. Forces were applied in the vertical axis by known masses, and in the two horizontal axes by a spring-loaded strain gauge. Accuracy was also checked by performing repeated trials with no contact made on the bag, integrating the force-time curves, and checking the difference of the integral to zero. The results are presented in the following chapter.

The subject was instructed to kick upon hearing a verbal command. As this command was given, a signal simultaneously triggered MacLab to record the force platform data from 1 s before until 5.5 s after this trigger. This was to give the subject time to retract the kick and then come back to rest with both feet completely on the force platform. When performing a maximal effort technique in any form of training or competition, Taekwon-Do practitioners are expected to retain balance during and after completion. Therefore, the condition that performers must begin and finish stationery is realistic. The target area on the bag was positioned at a height equal to the subject's abdomen, and at a distance that they deemed to be suitable for a turning kick.

High speed video.

In order to determine the duration of impact between the foot and the bag, a high speed Motion Analysis video camera sampling at 200 Hz with a shutter speed of 1 ms was zoomed in and focused on the target area of the punching bag. The camera was positioned at the same vertical height as the target and aligned perpendicular to the plane of motion of the foot immediately before impact so as to judge the instants of the beginning and end of contact accurately.

Three-dimensional videography.

Because the turning kick involves rotation about all three orthogonal axes, a three-dimensional approach was used. The process of recreating a three-dimensional object from two-dimensional images is called photogrammetric reconstruction (Ladin, 1995, pp. 9). It involves combining the information originating from projections of each point of interest on two (or more) cameras.

This study used two tripod-mounted Panasonic video cameras (model WV-CL350/A, Matsushita Communication Industrial Co. Ltd., Japan) operating at 50 fields per second, with a shutter speed of 2 ms. The cameras were gen-locked, so that the sampling of one camera (slave) was synchronised with the other (master). The Event Synchronisation Unit (Peak Performance Technologies, Englewood, CO) uses the master camera's video signal as the gen-lock source, and enables the slave camera to be synchronised with this signal.

The cameras were positioned diagonally in front and behind the subject respectively on the same side as their kicking leg, giving approximately a 90^{o}

between their respective optical axes. Each camera was also elevated about 2.5 meters and tilted down in order to get the image of the subject as large as possible while ensuring that all points of interest remained totally within the field of view throughout the entire movement. Spotlights illuminated the experimental space from behind the cameras, and a black curtain was positioned behind to provide contrast (see Figure 5). The sampling frequency of 50 Hz for the present study was validated by the pilot study outlined in Appendix D.

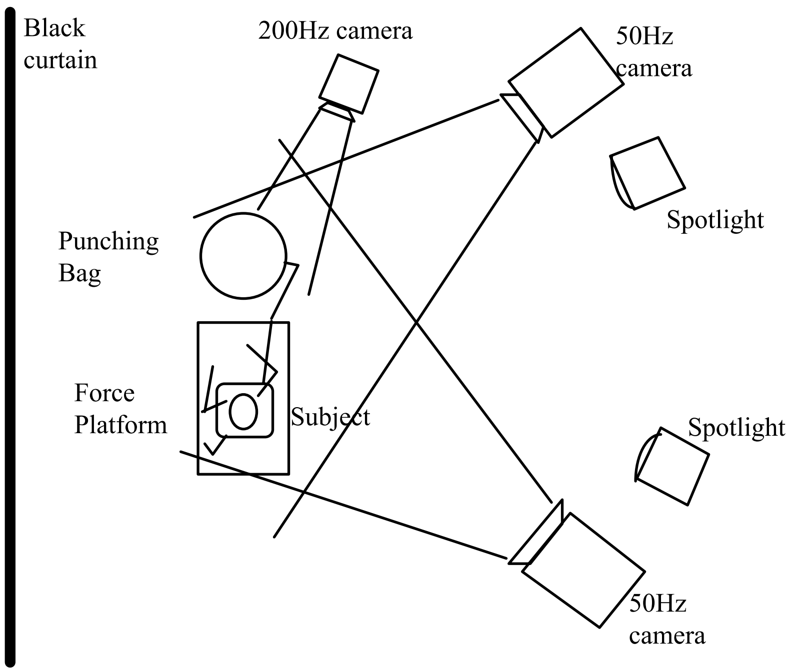


Figure 5. Overhead diagram of the data collection set-up.

The Peak E25 frame (Peak Performance Technologies, Englewood, CO) with 17 non co-planar points of known locations was used to calibrate the movement space. The frame filled approximately the same volume of space as the turning kick movement, and the point measurements are accurate to within 5 mm (Peak Motus Users Guide, 1996). Before every testing session the calibration frame was placed in the movement space so that all points were visible in both camera views, and then recorded for a brief period. Care was taken not to alter the cameras in any way after the calibration frame had been recorded.

Subjects wore tight fitting bike shorts and t-shirt, and had bare feet while kicking. White tape designed to reflect the projected light was attached to the subject at the third metatarsal phalangeal, ankle, knee, and hip joint centers of the kicking leg. These markers were later identified in the recorded images of the cameras, and used as a reference for visualising the respective joint centers. Because each joint was to be digitised from various perspectives, a marker placed at one point on the skin would not be representative of the joint center for the entire movement. Therefore, the reflective tape was attached around the circumference of the joint so as to help visualise the joint center from any perspective. This tape was attached securely but not so that it was uncomfortable or restricted the subject's movement in any way.

Subjects performed a 15 minute warm-up that they decided would best prepare them to perform maximal effort kicks. This typically included callisthenic exercises followed by ballistic and static stretches. When subjects felt both physically and mentally prepared they performed ten practise kicks against the bag, simulating testing conditions as closely as possible. Subjects were instructed to kick immediately after the verbal command of "kick" from the experimenter. Each subject performed five maximal effort turning kicks at the 15 cm square target, and video data of the performances were recorded. The experimenter verbally encouraged subjects to exert full effort while maintaining accuracy, and reminded them to assess each kick in order to pick the best one of the five. The best kick was that which the subject felt had the greatest impact force, while still contacting the bag within the marked target.

<u>Data Reduction</u>

Impulse.

The impulse made on the subject over the movement by ground reaction forces is equal to the impulse exerted by the bag on the foot during the impact according to the following logic. The system of interest is the entire body of the performer. At the beginning of the movement they are stationery with zero linear momentum. After they complete the kick and return back to a stationery position, their linear momentum is once again zero. Therefore, the change in momentum of the system (subject) is zero over the movement. On the basis of the "impulse-momentum relationship" outlined during the development of the deterministic model, the net impulse exerted on the system by external sources must therefore be zero. There are two external sources that exert forces on the system over the course of the movement, the bag and the ground. Consequently, over the duration of the whole movement, the impulse exerted by the bag on the foot (which is equal and opposite to that exerted by the foot and the bag), must equal the impulse exerted by ground reaction forces.

In order to remove the constant vertical force of the subject's body weight, the Y component of ground reaction force was first adjusted to zero. This set the subject's body weight as the baseline, so that the resultant impulse was due solely to the impact. Next, the impulse for each axis was determined by calculating the integral over the specified time interval. This interval was from just before the first noticeable change in force until just after it returns to baseline, determined visually, for each of the channels. The resultant linear impulse was then computed by vector addition of the three components of impulse.

Duration of impact.

A sampling rate of 200 Hz implies that the time between each frame is 5 ms. Consequently, impact duration was calculated by counting the number of frames from the start until the end of impact (defined in the section on phases and critical instants earlier in the chapter) and multiplying by 0.005s.

Kinematics.

The points on the calibration frame were digitised for both camera views using the Peak Motus system. Once the calibration points from the two camera views were digitised, the DLT parameters were determined and stored. The calibration accuracy of the movement space was tested by checking the difference between the computed and the known three-dimensional locations of the calibration points, and results are provided in the following chapter.

The video recordings of the trials selected as the best by each subject were digitised for each camera view from the start until the finish of the kick. The frame number that separated the two phases of the kick, when the kicking leg in its most flexed position, was marked during digitising so that it could be used for subsequent analysis. Where the view of a marker was obscured or was obviously unrepresentative of the joint center, its position was visually estimated. For each trial, the two sets of digitised coordinates of the selected body landmarks were combined using the DLT algorithm, and the corresponding three-dimensional coordinates determined.

To minimise the effect of digitising and other random errors, each dimension (x, y, and z) of each digitised point was smoothed using a Butterworth digital low-pass filter. The data was filtered at an optimal cut-off frequency proposed by Yu (1988). This method calculates an optimum cut-off frequency (F_c) directly from the sampling frequency (F_s) according to the formula:

$$F_c = (1.4845 + 0.1532\, F_s^{1/2})^2$$

The optimum cut-off frequency for the present study was 7 Hz (1 d.p).

The kinematic variables identified by the deterministic model were then computed. The smoothed coordinate data were differentiated, using the method of central differences, to give the linear velocities of the toe, ankle, knee, hip, and shoulder joint centers immediately before impact. The calculated velocities correspond to the midpoint of three rather than two displacement sample points, and therefore coincide with the instant of the sampled displacements. The following formula was applied to calculate velocity from displacement data:

$$v_i = \frac{d_{i+1} - d_{i-1}}{2\Delta t}$$

where v_i is the velocity of the ith point, d_{i+1} and d_{i-1} are the displacements of the i+1th and i-1th point respectively, and Δt is the time between samples. Because the first and last displacement data points in each trial do not have corresponding points on either side to input into the equation, the velocities must be extrapolated using three data points after and before the point of interest respectively. This is shown by the following equations:

for the first data point (i=1)

$$v_i = \frac{(-d_{i+2} + 4d_{i+1} - 3d_i)}{2\Delta t}$$

for the final data point (i=n)

$$v_i = \frac{(d_{i-2} - 4d_{i-1} + 3d_i)}{2\Delta t}$$

The angular velocities at the ankle and knee joints, and the angular velocities of the thigh relative to, and projected onto, the horizontal plane were derived in the same manner from angular displacement data, as shown by the following equations.

for the middle data points

$$\omega_i = \frac{\theta_{i+1} - \theta_{i-1}}{2\Delta t}$$

for the first data point (i=1)

$$\omega_i = \frac{(-\theta_{i+2} + 4\theta_{i+1} - 3\theta_i)}{2\Delta t}$$

for the final data point (i=n)

$$\omega_i = \frac{(\theta_{i-2} - 4\theta_{i-1} + 3\theta_i)}{2\Delta t}$$

where ω is the angular velocity, θ is the angular displacement, and t is the again the time between samples. The accuracy of the digitising was tested by redigitising the videotape data from one trial to produce a second set of 3D raw coordinates for each camera, from which a set of identical kinematic variables were calculated. The raw coordinates from camera one of the original trial were combined with those from camera two for the redigitised trial to produce a third set of variables. A forth set was calculated by the combining the raw coordinates from camera two of the original trial with those from camera one of the redigitised trial. Four sets of kinematic data were thus computed from two digitised trials. The mean of the four sets of each kinematic variable was calculated to give the best estimate of the true value. The absolute differences between this estimated true value and the respective data sets were calculated. Relative differences were also calculated by dividing the absolute differences by the estimated true values and multiplying by 100.

Data Analysis

Impact force was calculated by dividing the impulse measured by the force platform by the duration of impact determined by high speed video. Correlations of each of the kinematic variables with impact force were calculated. The $\alpha = 0.05$ level of probability was selected as the indicator of the statistical significance of the correlation coefficients. For the kinematic variables a one-tailed test was selected, as, due to previous studies, a positive correlation was expected. Therefore a Pearson Product-Moment correlation coefficient of $r > 0.44$ ($n = 15$, d.f. $= 13$) was required to show a correlation significantly greater than zero. For the correlation coefficients of impulse and duration of impact, a two-tailed test was selected as it was uncertain whether a positive or negative correlation would be evident. Therefore, $r > 0.51$ was required for significance.

The power of a statistical test is the probability that it will yield statistically significant results (Cohen, 1988, pp. 1). From previous studies (Pieter & Pieter, 1995; Sidthilaw, 1997), it was expected that some correlation coefficients may be 0.60 or greater. For the one-tailed tests, such a result would have a power of 81%, and for the two-tailed test it would be 70%.

Chapter 4

Results and Discussion

Sources of Error

Error in Calibration

The mean square (MS) error is the distance between the measured and computed points, and provides a representative measure of the intrinsic error of that particular camera configuration and arrangement (Peak Motus Users Guide, 1996). The object space percent (OS %) error is the average mean square as a percentage of X, Y, Z, and resultant position. The MS error and OS % error are calculated for each of the XYZ axes and the resultant position. In general, errors of up 0.5% of the object space are considered acceptable (Peak Motus Users Guide, 1996). The MS errors and OS % errors for the two data collection sessions are given in Table 1.

Table 1

Error in Calibration

	X	Y	Z	Position
Session 1				
MS Error (m)	0.0018	0.0014	0.0020	0.0031
OS % Error	0.1502	0.1363	0.2283	0.1673
Session 2				
MS Error (m)	0.0020	0.0018	0.0020	0.0033
OS % Error	0.1661	0.1667	0.2260	0.1817

For both sessions the resultant position errors were within 3.5 mm, which corresponds to less than 0.2% of the object space. Therefore, the accuracy of the calibration was considered acceptable.

Error in Force Platform

As dictated by the impulse-momentum relationship outlined in the development of the deterministic model, if a subject follows the normal experimental procedure (see data collection section) but does not make contact with the bag, the resultant impulse recorded by the force platform for the movement should be equal to that caused by body weight over the duration of the movement. If the vertical ground reaction force component is adjusted to zero for body weight, then the resultant impulse should be zero. This was tested for five kicks by one of the subjects (#2), and the results are presented in Table 2.

The mean resultant error of 2.22 N.s was 6.8% of the mean impulse recorded during the data collection (see results section). The total duration of the kick was usually around 3 seconds, thus the impulse error recorded corresponds to less than 1 N of error per second. Error in impulse measurement was thus deemed to be negligible.

Table 2

Error in Impulse Measurement

Trial #	X (N.s)	Y (N.s)	Z (N.s)	Resultant (N.s)
1	2.06	-0.31	-1.52	2.58
2	0.12	1.61	1.27	2.06
3	-0.88	-2.01	1.90	2.90
4	0.28	0.44	0.27	0.59
5	1.98	-0.19	-2.20	2.97
Mean Error	0.71	-0.09	-0.06	2.22
S.D.	1.14	1.18	1.58	0.88
Maximum	2.06	1.61	1.90	2.97
Minimum	-0.88	-2.01	-2.20	0.59

Error in Digitising

The videotape data from one trial (#2) was redigitised, and four sets of the kinematic data were computed as outlined in the kinematic data reduction section in the previous chapter. The mean of the four sets of each kinematic variable was calculated to give the best estimate of the true value, and this was compared to the four data sets. The mean absolute and relative differences of each 3D kinematic variable are presented in Table 3.

Table 3

Reliability of the Kinematic Variables

Variable	Mean Absolute error	Relative Error
Linear speed of the toe	0.03 m/s	0.18%
Linear speed of the ankle	0.36 m/s	2.59%
Linear speed of the knee	0.32 m/s	21.37%
Linear speed of the hip	0.16 m/s	18.60%
ΔAngular Speed at Ankle 1	38.04 deg/s	42.58%
ΔAngular Speed at Ankle 2	85.14 deg/s	34.16%
ΔAngular Speed at Knee 1	22.96 deg/s	17.27%
ΔAngular Speed at Knee 2	123.33 deg/s	6.78%
ΔAngular Speed at Hip_{ele} 1	16.29 deg/s	3.97%
ΔAngular Speed at Hip_{ele} 2	51.20 deg/s	7.15%
ΔAngular Speed at Hip_{hor} 1	9.61 deg/s	1.21%
ΔAngular Speed at Hip_{hor} 2	52.27 deg/s	8.29%

The relative errors of the linear velocities of the toe and ankle immediately before impact were both within 3% of the estimated true values and thus considered acceptable. The higher relative errors of the linear velocities of the knee and hip seems partly due to the mean values value being relatively small which would necessarily elevate the relative error (Hay & Yu, 1995); the absolute errors were both smaller than that at the ankle. The relative errors of the changes in angular velocity at the knee and hip joints were within 10% with the exception of Knee 1. Once again, this variable had a smaller absolute value which inflated the relative errors. The high relative errors for the changes in angular velocity at the ankle over Phases 1 and 2 were of little concern as neither of these variables was of interest in the proceeding analysis.

Descriptive Data

Impact Forces

The values obtained for resultant linear impulse, duration of impact, and average impact force are given in Table 4. Means, standard deviations, and maximum and minimum values are provided here; data for individual subjects can be found in Appendix E.

Table 4
Resultant Linear Impulse, Duration of Impact, and Average Impact Force Data for the Group.

Subject	Resultant Linear Impulse (N.s)	Duration of Impact (s)	Average Impact Force (N)
Mean	32.2	0.11	292
S.D.	8.0	0.02	54
Maximum	45.9	0.15	382
Minimum	18.6	0.08	180

The mean linear impulse exerted by the foot on the bag of 32.2 N.s was significantly greater than impulses recorded by Shibayama & Fukashiro (1997) for the Karate punch, where values ranged from 9 to 18 N.s. However, in that study impulse was measured from the beginning of contact to 0.01 s after the force reached its peak. If the fist was still in contact with the target after this time, some of the impulse exerted would not have been recorded. Nevertheless, it seems reasonable to expect that the impulse exerted by a kick would be somewhat greater than that exerted by a punch due to the greater mass of the leg. Impulse readings were less than those obtained by Sidthilaw (1997) for Thai boxing middle roundhouse kicks. The mean impulse and standard deviation recorded in that study was 50.2±19 N.s, nearly 20 N.s higher than the mean obtained in the present study. Reasons for this are similar to those given below for the differences in force readings, especially with regard to variations in technique. When performing the roundhouse kick, Thai boxers attempt to travel directly through their target without withdrawing the foot as is done in Taekwon-Do. Thus the foot and the bag stay in contact together longer which would contribute to the greater impulses recorded.

The mean duration of impact recorded was 110 ms, which was approximately ten times greater than those recorded when kicking a ball; typically in the range of 8 to 15 ms. This is to be expected as the bag used in the present study was far more elastic than a soccer ball which would cause the foot to remain in contact for a longer time. Unfortunately, no other researchers have investigated the impact duration for martial arts kicking.

As outlined in the review of literature, the comparison of forces between studies must be done with caution due to varying measurement techniques. The mean value of average impact forces over the duration of impact recorded in the present study was 292 N, with the maximum reaching 382 N. Conkel et al. (1988) found impact forces of up to 470 N, and Pieter & Pieter (1995) recorded 519±96 N, both of which were higher than the forces registered in the present study. This may be due to a number of factors. Firstly, the other studies did not specify whether they were measuring peak, average, or some other form of "impact force", and this is an important distinction. Another possible reason for this includes all previous studies testing more highly trained subjects, often of an

Olympic level. Such athletes train almost full-time, which makes it not surprising that their values were significantly higher than those of the subjects in the present study, who typically train 2-3 times per week. Another possible reason for the differences is the variation in kicking technique. In all of the above studies, the authors termed the kick "round kick". Such a kick is typically performed in the same motion as a turning kick, but uses the instep instead of the ball of the foot to contact. Subjects using the ball of the foot as in the present study might have performed the kick at slightly less than maximal effort for fear of injuring their toes on the bag. Also, the nature of the target may also have been a factor. All of the above studies used targets that were larger than what was used for the present one. As the accuracy requirement increases, a corresponding decrease in impact force would be expected. The inertia and elasticity of the target is another factor that influences the measurement of impact force. A heavier, more rigid target, such as a heavy punching bag or padded fixed surface, would allow a subject to record a greater impact force.

Kinematics

The linear velocities of the toe, ankle, knee and hip immediately before impact are given in Table 5. A summary of the mean, standard deviation, and maximum and minimum values of each variable is provided, and the data of individual subjects can be found in Appendix E. Figure 6 shows the time course of the linear velocities of the joints from start of the kick until immediately before impact, averaged for all of the subjects.

Table 5

Linear Velocities of the Joints of the Kicking Leg Immediately Before Impact

Subject	Toe Vel. (m/s)	Ankle Vel. (m/s)	Knee Vel. (m/s)	Hip Vel (m/s)
Mean	13.4	12.1	2.11	0.69
S.D.	1.6	1.1	0.84	0.28
Maximum	16.0	14.0	3.31	1.40
Minimum	10.4	10.3	0.20	0.40

The mean linear velocity of the foot immediately before impact of 13.4 m/s was within the expected range for this group of athletes, based on previous research. Table 6 compares the results with three other studies on the Taekwon-Do turning kick.

The mean values for the peak linear velocities recorded over the subjects in the present study were lower than all of the other studies. The possible reasons for this result are similar to those suggested in the above paragraph on kicking force, namely other studies involving a) more highly trained athletes, b) the "round kick" instead of the turning kick, and c) a smaller accuracy requirement.

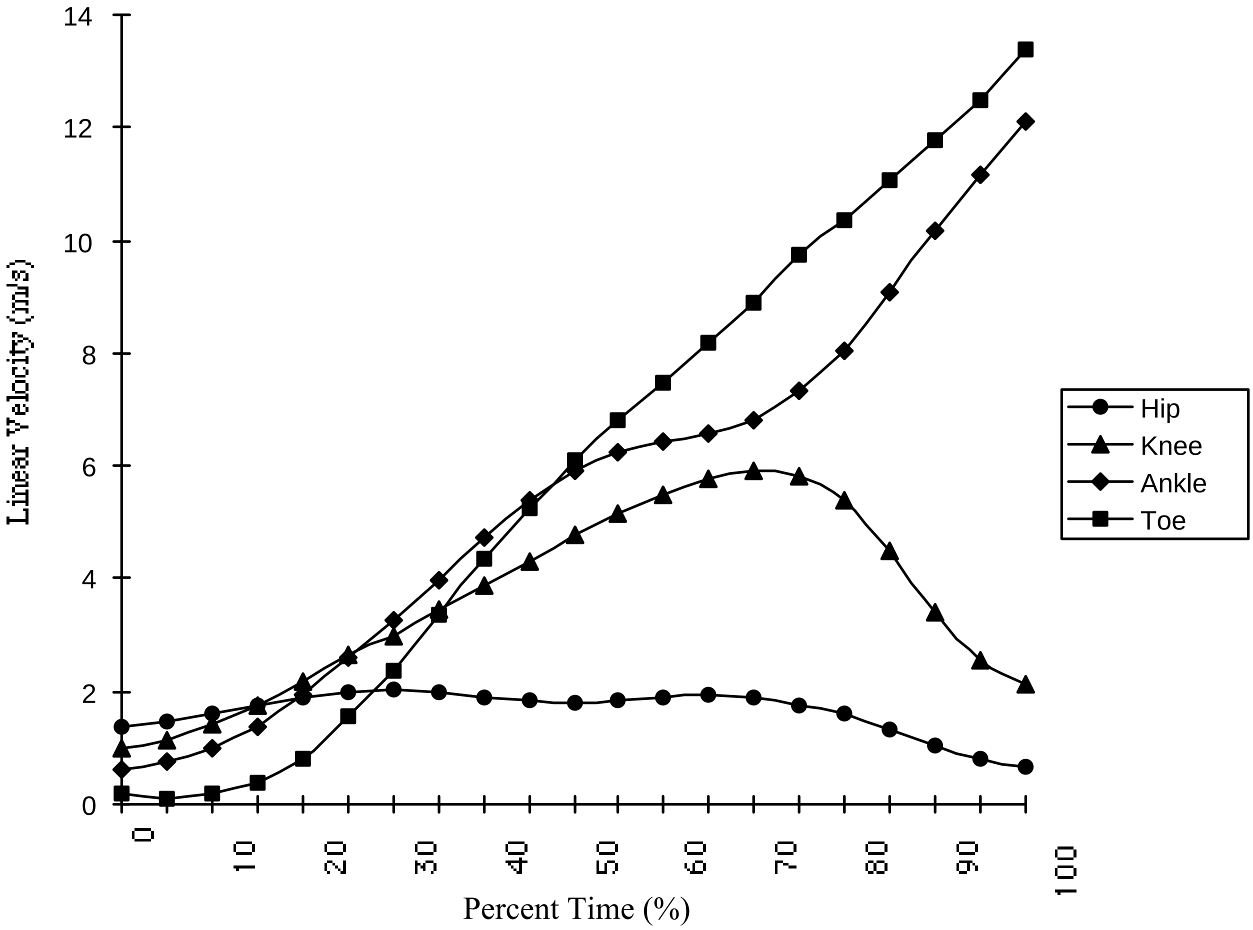


Figure 6. Average linear velocities of the joints of the kicking leg.

Table 6

Mean Peak Linear Velocities obtained for the Foot during the Turning or Roundhouse Kick

Author/s and year	Type of subjects	Mean peak linear velocity of foot (m/s)
Conkel et al. (1988)	Elite males and females	14.6
Serina & Lieu (1991)	Male black-belts	15.9
Pieter & Pieter (1995)	Elite males	15.5
Pearson (1997)	Expert males	13.4

Because previous research has tended to focus on the linear velocity of the foot, there is limited data with which to compare the ankle, knee, and hip values. It seems reasonable that the peak linear velocity of the ankle is marginally lower than that at the toe (1.3 m/s in the present study), due to the toe rotating about the axis (in this case the knee joint) at a greater radius than the ankle. Like the toe, the linear velocity of the ankle reached its peak in the last frame before impact. Sidthilaw (1997) measured the mean linear velocity of the ankle immediately before impact for the Thai boxing middle roundhouse kick to be 7.1 m/s, which was substantially lower than that found in the present study. It should be noted that all Thai boxing subjects recorded their maximum velocities of the ankle (around 10 m/s) approximately 0.10 s before impact, and not in the last frame before impact. This possibly reflected an emphasis on maintaining accuracy.

The mean linear velocities at the knee and hip immediately before impact of 2.11 m/s and 0.69 m/s respectively were not their maximum values, as shown in Figure 6. Serina & Lieu (1991) found knee and hip linear velocities were a up to 8% and 3% respectively of the magnitude of linear velocity of the toe. Therefore, when developing their linkage models, they assumed both joints to be completely stationery immediately before impact. The present study found mean linear velocities of the knee and hip immediately before impact corresponded to 15.7% and 5.1% of linear velocity of the toe. Both values were notably higher than those found by Serina & Lieu, reflecting possible differences in technique used. This includes the possibility that subjects in their study made first contact with the target at a relatively later stage in the kicking motion.

The changes in angular velocities at the ankle and knee joints are given in Table 7. The first value for each joint is the change in angular velocity over the first phase, and the second value is the change over the second phase (see the section on phases and critical instants for definitions). The time course for the angular velocities over the movement, averaged for all subjects, is given in Figure 7.

The foot and shank have previously been combined as a single rigid segment for kicking analyses (Serina & Lieu, 1991; Putnam, 1991; Sidthilaw, 1997), demonstrating the relatively small role that the ankle joint plays in contributing to kicking performance. The relatively large standard deviations confirm the variability of this measure, and preclude any meaningful analysis.

Table 7

Changes in Angular Velocity at the Ankle and Knee Joints over Phases 1 and 2

Subject	Δ Angular Vel. at Ankle (degrees/s)		Δ Angular Vel. at Knee (degrees/s)	
	Phase 1	Phase 2	Phase 1	Phase 2
Mean	-243	199	56	1570
S.D.	218	258	154	338
Maximum	66	714	386	2302
Minimum	-703	-277	-187	1027

The changes in angular velocity at the knee are more suited to reasonable interpretation. The mean change in angular velocity during the first phase of 56 deg/s (0.98 rad/s) was relatively small. This was expected, as the angular velocity at the knee should be close to zero both at the start of the kick and at the point of maximum knee flexion. During the second phase, the change was much larger, with a mean value of 1570 deg/s (27.4 rad/s). This shows that the shank was vigorously extending relative to the thigh during the final phase before impact (about 0.10 s duration), and in all cases the maximum angular velocity at the knee was recorded in the last frame before impact. Although no similar data has been collected for the turning kick, peak angular velocities at the knee of about 1400 deg/s (24.4 rad/s) have been recorded for the front kick (Park, 1989), and up to 2120 deg/s (37 rad/s) for kicking a ball (Putnam, 1983). Therefore, the data collected here seems reasonably consistent with previous studies. The source of this angular velocity is of interest as such a high angular velocity seems too large to have been generated solely by muscular knee extensor moments.

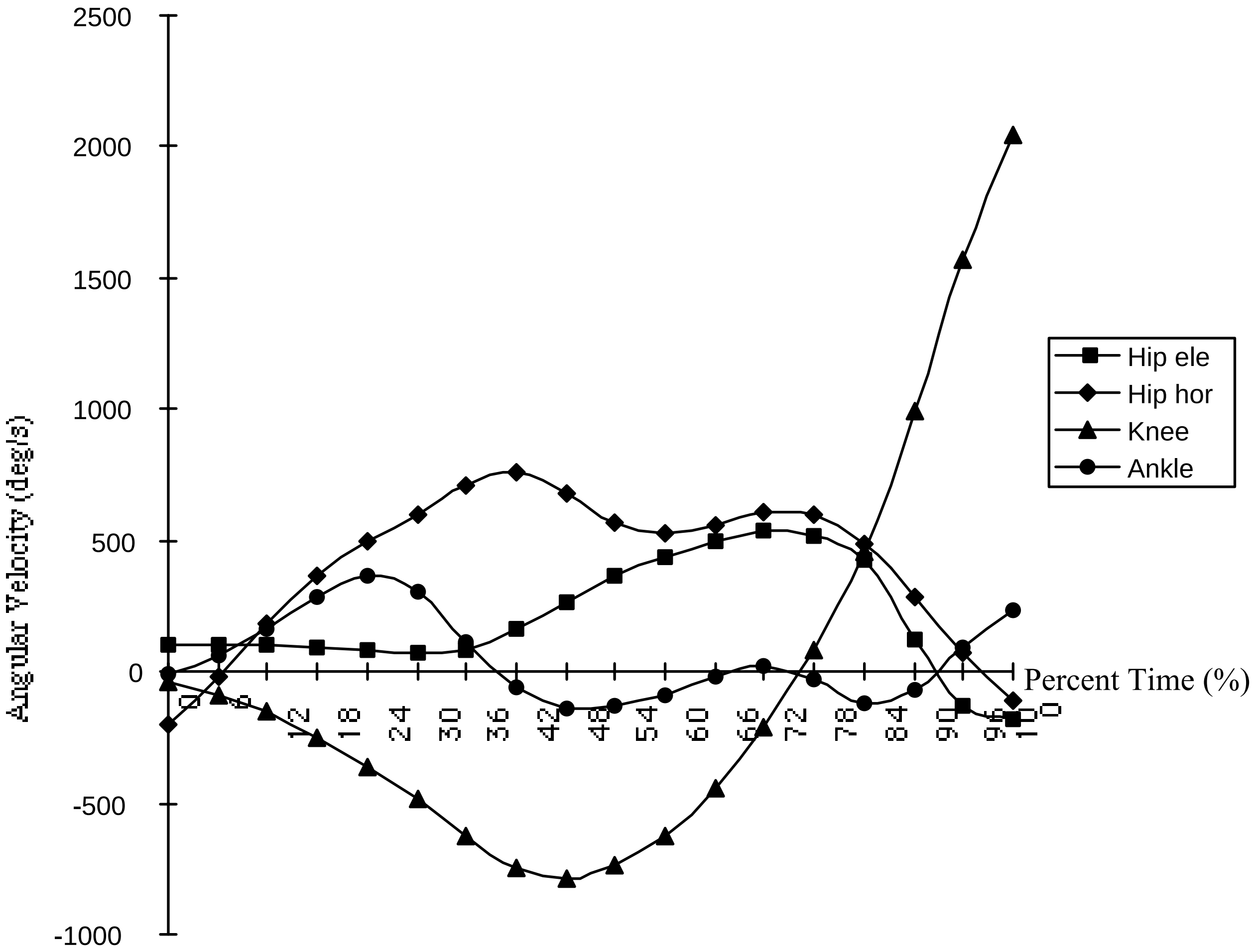


Figure 7. Average angular velocities at the joints of the kicking leg.

Because of the more complicated three-dimensional nature of the hip joint, the angular velocity data are presented as two components of the resultant velocity vector. The changes in angular velocity at the hip joint are given in Table 8. Results are provided for the rate of change in the included angle made between the thigh and the horizontal plane (Hip_{ele}) and the rate of change of the angle that the projection of the thigh onto the horizontal plane made with the Y axis (Hip_{hor}) for Phases 1 and 2.

Table 8

Changes in Angular Velocity at the Hip

Subject	Δ Angular Vel. at Hip_{ele} (degrees/s)		Δ Angular Vel. at Hip_{hor} (degrees/s)	
	Phase 1	Phase 2	Phase 1	Phase 2
Mean	408	-586	663	-543
S.D.	148	276	147	190
Maximum	684	-138	946	-257
Minimum	142	-1100	358	-959

The changes in angular velocity at the hip for both elevation and horizontal rotation showed the same general trends. Both demonstrated a large positive change over Phase 1, and a similarly large negative change over Phase 2. For the elevation hip angular velocity there was a net negative change. If it is assumed that there was little or no rotation occurring at the start of the kick, this means that the thigh was rotating slightly downwards immediately before impact. For horizontal hip angular velocity, there was a net positive change, which similarly means that the thigh was rotating slightly towards the bag immediately before impact.

The large increases in angular velocity at the hip over Phase 1 and subsequent decreases over Phase 2 provides some clues as to how the very large changes in knee angular velocity over Phase 2 in Table 7 were generated. Sorenson (1996) concluded that about one-third of lower leg angular acceleration during the execution of a front kick was caused by a knee extensor muscular moment, and the remaining two-thirds was due to a motion-dependent moment caused by thigh angular velocity. This interaction between segments during kicking has been investigated by Putnam (1983; 1991; 1993), who outlines the summation of speed principle where angular motion is transferred from proximal to distal segments to help create a large linear speed at the foot. As the angular speed of the distal segments increase, there is a corresponding decrease in angular speed for the proximal segments, indicating that a transfer of angular momentum has occurred.

In the present study, the large decrease in the angular velocity at the hip corresponded to the large increase in angular velocity at the knee. This suggests that a transfer of momentum has occurred in the manner proposed above. In order to further investigate this, Pearson Product Moment correlation coefficients were computed between the changes in velocity at the knee and those at the hip, both for elevation and horizontal rotation. A correlation coefficient of $r = -0.90$ was found between the change in angular velocity at the knee during Phase 2 and the change in horizontal angular velocity at the hip during Phase 2. Hence, decreases in horizontal angular velocity at the hip were strongly associated with increases in angular velocity at the knee towards the last part of the kick. Although not fully investigated here, it should also be noted that in every case the maximum linear velocity of the hip preceded that of the knee which in turn preceded the maximum of the toe. This seems to add further support to the notion of proximo-distal sequencing.

Correlational Analysis

The Pearson Product Moment correlation coefficients between impact force and impulse, duration of impact, and body mass are given in Table 9. Impulse was highly correlated with impact force ($r = 0.73$), and the scatter plot of impulse against impact force is given in Appendix F1. Pieter (1994) states that the magnitude of the momentum generated (and thus impulse exerted) by a technique is directly related to the likelihood of it causing a cerebral concussion. A positive relationship between impulse and impact force seems obvious due to the former being calculated directly from the latter, however, as shown when the deterministic model was developed, a trade-off exists with the duration of impact. A push that displaces the bag a great deal might record a high impulse value, but due to the long duration of push it would result in a low average impact force. Consequently, an inverted parabolic, rather than a positive linear, relationship should result. One possible reason why this was not found was that all subjects that participated in the present study were trained to retract the kick after impact, thus none had a particularly long duration of impact.

Similarly, this is one probable reason for the lack of any significant positive or negative correlation between duration of impact and impact force. Comparing subjects that had been trained in different ways, and therefore giving a greater range of values, may yield more significant results.

Table 9

Correlations of Impulse, Duration of Impact, and Body Mass with Impact Force

Variable	Correlation coefficient (r)
Impulse	0.73*
Duration of Impact	-0.05
Body Mass	0.72*

Note. * denotes significance at the 5% level

A strong positive correlation of r = 0.72 was found between mass of the foot and impact force. The mass of the foot is taken to be proportionally representative of the body mass, as outlined during the development of the deterministic model. The scatter plot of body mass against impact force is provided in Appendix F2. This significant correlation was consistent with previous research, where correlation coefficients have reached as high as r = 0.94 (Pieter & Pieter, 1995). This significant result points to body mass as one possible source of confounding error in the correlational analysis of the kinematic variables. Increases in force due to greater body mass could potentially have hidden significant correlations with other kinematic variables, or weakened those identified as significant. Future research should consider standardising impact force for body mass, while keeping in mind that absolute force is the more realistic measure of the effectiveness of the kick.

The correlations between impact force and the linear speeds of the toe, ankle, knee, and hip immediately before impact are given in Table 10. Linear speed of the toe and ankle immediately before impact were found to significantly correlate with impact force (r = 0.68 and r = 0.66 respectively), while linear speed of the knee and hip were found not to. The scatter plots for the linear speeds of the toe and ankle immediately before impact against impact force are given in Appendices F3 and F4. The significant findings for the toe and ankle replicated the results of Pieter & Pieter (1995) who found a correlation coefficient between impact force and foot speed for the turning kick of $r = 0.72$, and Sidthilaw (1997) who found a $r = 0.79$ correlation coefficient between linear speed of the ankle and impact force. Thus, the link from impact force down to toe and ankle speed in the deterministic model seems to have been validated. Where the goal of the kick is maximum impact force, the Taekwon-Do practitioner should be encouraged to generate a high linear velocity of the foot. Methods for accomplishing this in terms of technique have been discussed earlier in the chapter with regard to the summation of speed principle. In training, drills to increase foot speed should be emphasised.

The finding that knee and hip linear speed immediately before impact were uncorrelated to impact force was anticipated, as previous research (Serina & Lieu, 1991) has assumed both to be zero, and thus not contributing, at this instant. A negative correlation could almost be expected, as higher linear speeds of these two variables would tend to point to a less efficient transfer of angular momentum to distal segments according to the summation of speed principle. Similar to the discussion on resultant linear impulse and duration of impact correlations, a more diverse range of martial artists that had been trained differently would be needed to fully investigate such a hypothesis.

Table 10

Correlations of Linear Speeds with Impact Force

Variable	Correlation coefficient (r)
Linear Speed of Toe	0.68*
Linear Speed of Ankle	0.66*
Linear Speed of Knee	0.19
Linear Speed of Hip	-0.07

Note. * denotes significance at the 5% level

Correlations of impact force with changes in angular speed at the ankle, knee, and hip joints are displayed in Table 11. The only variable to significantly correlate with impact force was the change in angular velocity at the knee over Phase 2 ($r = 0.48$). The scatter plot is provided in Appendix F5. Results indicated tentatively that greater rates of knee extension at the end of the kick were associated with increases in impact force. It must be remembered when applying this finding that, according to the summation of speed principle discussed earlier, a large angular speed at the knee is due to the angular deceleration at the hip as well as a knee extensor moment. Accordingly, the coordination of the movement should be stressed. Likewise, prescribed resistance and plyometric training should emphasise multi-joint coordinated exercises.

No significant correlations of any of the changes in angular velocities at the hip with impact force were found. Positive correlations of either elevation or horizontal hip change in angular velocity over Phase 1, or negative correlations over Phase 2 would have lent further support to the summation of speed principle, but this was not the case.

Table 11

Correlations of Changes in Angular Speeds with Impact Force

Variable	Correlation coefficient (r)
Change in Angular Speed at Ankle 1	-0.22
Change in Angular Speed at Ankle 2	0.44
Change in Angular Speed at Knee 1	0.13
Change in Angular Speed at Knee 2	0.48*
Change in Angular Speed at Hip_{ele} 1	-0.12
Change in Angular Speed at Hip_{ele} 2	0.26
Change in Angular Speed at Hip_{hor} 1	0.25
Change in Angular Speed at Hip_{hor} 2	-0.32

Note. * denotes significance at the 5% level

Correlations of impact force with segment lengths are given in Table 12. All segment lengths had positive correlations with impact force, and the value for thigh length was significant (r = 0.46). The scatter plot is given in Appendix F6. This demonstrates a general trend of significant correlation between leg length and impact force. This seems reasonable as the segment lengths act as the radius which, together with the angular velocity at the joint, determines the linear velocity of the distal points.

Table 12

Correlations of Segment Lengths with Impact Force

Variable	Correlation coefficient (r)
Foot Length	0.29
Shank Length	0.24
Thigh Length	0.46*

Note. * denotes significance at the 5% level

Conclusion

The following conclusions can be drawn from the present study:

1. This study recorded the kinematics of Taekwon-Do turning kicks performed by recreational practitioners, and these were reasonably consistent with those recorded by previous studies.

2. The turning kick was seen to display the proximo-distal sequence of segment rotations, or the so-called summation of speed principle. It was evident from the video data collected during this experiment that the proximo-distal sequence appears to begin with trunk rotation. Further studies should therefore include the trunk in the analysis, and also quantify the contribution of this summation of speed to the impact force or some other appropriate outcome.

3. The significant positive correlation of the peak linear velocity of the ankle and toe (ie. foot) with impact force of the turning kick replicated previous research. Taekwon-Do practitioners attempting to develop larger impact forces for their turning kicks should be encouraged to practice drills to increase their foot speed immediately before impact.

4. Subjects with greater body mass generated larger impact forces. This was identified as a possible confounding factor in the correlational analysis for the kinematic variables. Further studies should consider standardising impact force of kicks for body weight, depending upon the purpose of the analysis.

5. There was tentative evidence provided that thigh (and hence leg) length is related to the impact force of turning kicks, but this should be confirmed by more specific research.

Implications

When performing a maximal effort turning kick, practitioners should emphasise the sequential pattern of motion, beginning with flexion and abduction of the hip, and finishing with rapid extension of the knee.

Training implications are that athletes should concentrate on developing foot speed immediately before impact. Further studies could investigate the effectiveness of training methods such as resistance training, plyometrics, or simple line drills.

Practitioners may consider trying to increase their mass if they wish to increase the impact force of their kick, so long as this does not result in a reduced speed of the foot. It must be remembered that sparring competitors are divided by body weight, and moreover agility may be compromised by weight gains.

Sparring competition divisions should continue to be determined according to body mass as well as rank. There is also possible evidence that competitors should be separated by height also.

Recreational practitioners produced linear velocities comparable to those recorded in previous studies that were deemed to possess a high injury potential. Taekwon-Do instructors should bear this in mind during sparring practice, especially when no protective gear is being worn.

Chapter 5

Summary

Taekwon-Do is a form of self-defence noted for its powerful kicking techniques. The turning kick is the most frequently used in Taekwon-Do competition, yet has been the subject of few scientific studies. The kinematics of the turning kick are yet to be fully described, and the contribution of these kinematics to the impact force is yet to be quantified. The purposes of the present experiment were a) to describe the kinematics of Taekwon-Do turning kicks, and b) to determine those kinematic variables that were most closely related to large impact forces in turning kicks. It was hypothesised that at least one of the kinematic variables identified would positively correlate with impact force, and the so-called summation of speed principle would be seen to apply to the turning kick.

In order to test these hypotheses, a deterministic model of the impact force of the turning kick was developed. Fifteen subjects completed maximal turning kicks against a suspended punching bag, and impulse, duration of impact, and three-dimensional kinematic data were collected. Impulse was measured by integrating the force-time curve obtained from a force platform, and duration of impact recorded by a high speed video camera zoomed and focused on the target area of the bag. The three-dimensional kinematics were obtained using the Peak Motus System that uses the DLT algorithm to obtain three-dimensional data from the images of two video cameras. Impact force was calculated by dividing impulse by duration of impact, and the linear and angular speeds were derived from the three-dimensional position data. Analysis involved a correlational analysis between impact force and the variables identified in the deterministic model.

The mean impact force obtained was 292 N, and the impulse and duration of impact means were 32.2 N.s and 0.11 s respectively. Impact forces recorded appeared lower than those reported elsewhere, but a number of possible reasons for the discrepancies were suggested. Linear velocity of the toe immediately before impact had a mean of 13.4 m/s, which was slightly lower than those recorded in previous studies on elite athletes. Linear velocities of the ankle, knee, and hip immediately before impact had mean values of 12.1 m/s, 2.11 m/s, and 0.69 m/s respectively. Changes in angular velocities at the ankle and knee were -243 deg/s and 56 deg/s over Phase 1 and 199 deg/s and 1570 deg/s over Phase 2. Changes in angular velocity of the thigh relative to the horizontal plane and the thigh projected onto the horizontal plane were 408 deg/s and 663 deg/s over Phase 1, and -586 deg/s and -543 deg/s over Phase 2. The large angular velocities at the knee during the last part of the movement corresponded with a large decrease in the angular velocities at the hip, which lent support to the summation of speed principle. A correlation coefficient of $r = 0.90$ was found between angular velocity at the knee during Phase 2 and angular velocity of the thigh projected onto the horizontal plane during Phase 2, which lent further support to this interpretation. Moreover, peak linear velocity of the hip preceded that of the knee which preceded that of the toe in all cases, further implying a proximal to distal sequence of motion.

A significant correlation ($r = 0.73$) was found between impulse and impact force but not between duration of impact and impact force, and this was discussed with regard to similarities between the subjects' technique. Body mass was significantly correlated with impact force, which was consistent with previous findings. The linear speeds of the toe and ankle immediately before impact were significantly correlated with impact force ($r = 0.68$ and $r = 0.66$), but the linear speeds of the knee and hip were not. For the changes in angular speeds, only that of the knee over Phase 2 was significantly correlated with impact force ($r = 0.48$). Recommendations based upon these results centred upon coordinating the movement so as to maximise the effect of the summation of speed principle, and training to increase the foot speed immediately before impact. Thigh length was also found to positively correlate with impact force ($r = 0.46$).

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Appendices

Appendix A

Kinematics and Kinetics of the Taekwon-Do Turning Kick

INFORMATION SHEET FOR PARTICIPANTS

Thank you for showing an interest in this project. Please read this information sheet carefully before deciding whether or not to participate. If you decide to participate we thank you. If you decide not to take part there will be no disadvantage to you of any kind and we thank you for considering our request.

The aim of this project is to answer the question of what contributes to a more forceful turning kick. Once those variables that have a high influence on the impact force of the turning kick are determined, technique and training methods can be optimised. Therefore, this study will examine the contribution of selected biomechanical parameters to the impact force of the turning kick. This study will partially fulfil the requirements for an Honours degree in Physical Education for the researching student.

Should you agree to take part in this project, you will be asked to:

- Complete a subject information sheet, including: name, age, and training experience;
- Wear bike shorts that are supplied;
- Have reflective markers attached to the joint centers on your kicking leg and shoulder;
- Warm up and stretch for 15 minutes or until you feel ready, including at least 10 practice kicks against a punching bag;
- Complete 5 repetitions of maximal force turning kicks against a stationery punching bag, starting and finishing in a stationery position on a mounted force platform.

Each testing session will last about one hour. Your weight and height will be measured, then the lengths of the segments of your kicking leg. You will then perform the testing as outlined above while being videotaped. This video data will then be analysed to calculate linear and angular velocities, and duration of impact, and the force platform data integrated and summed to calculate impact force.

Please be aware that you may withdraw from the project at any time with out any disadvantage to yourself of any kind.

Taekwon-Do kicks involve rapid accelerations and decelerations of the legs. If you have any injuries or health problems that could be worsened by participating in this study, you will not be able to part in this study because of the unacceptable risk to all concerned.

The information obtained in this study will be securely stored and available only to Jake Pearson, Dr Toshimasa Yanai, and the two members of Jake Pearson's supervisory committee. All videos and experimental data will be destroyed after the completion of the study except that, as required by the University's research policy, any raw data on which the results of the project depend will be retained in secure storage for five years, after which it will be destroyed.

Results of this study may be published but any data included will in no way be linked to any specific participant. You are most welcome to request a copy of the results of the project should you wish. If you decide to take part, please read and sign the consent form and give it to Jake Pearson.

If you decide to take part, please read and sign the consent form and give it to Jake Pearson.

If you have any questions about our project, either now or in the future, please feel free to contact either:-

Jake Pearson	or	Dr Toshimasa Yanai
School of Physical Education		School of Physical Education
Phone 4799114		Phone 4798981

This project has been reviewed and approved by the Ethics Committee of the University of Otago.

<u>Appendix B</u>

Kinematics and Kinetics of the Taekwon-Do Turning Kick

CONSENT FORM FOR PARTICIPANTS

I have read and I understand the information sheet for volunteers participating in this study. I have had the opportunity to discuss the study and to ask questions, which have been answered to my satisfaction.

I know that:-

1. my participation in the project is entirely voluntary;
2. I am free to withdraw from the project at any time without any disadvantage;
3. the data obtained in this study will be destroyed at the conclusion of the project but any raw data on which the results of the project depend will be retained in secure storage for five years, after which it will be destroyed;
4. if I do get injured or my health suffers as a direct result of taking part in this study, the costs of treatment and any compensation will be covered by ACC regulations;
5. the results of the project may be published but my anonymity will be preserved.

I .... (full name) hereby consent to take part in this study.

Signature: ....

Date: ....

I wish to receive a copy of the results Yes / No

Appendix C

Table C1

Subject Data for Age, Taekwon-Do Training Experience, Height, Body Mass, and Body Segment Lengths

Subject #	Age (yrs)	Exp. (yrs)	Height (m)	Mass (kg)	Segment Lengths (m) Foot	Shank	Thigh
1	26	12	1.74	82.2	0.175	0.42	0.44
2	22	10	1.83	72.0	0.180	0.43	0.43
3	24	6	1.74	65.2	0.165	0.43	0.41
4	18	2	1.72	58.1	0.170	0.40	0.41
5	20	2.5	1.76	62.4	0.160	0.43	0.43
6	21	3.5	1.84	75.4	0.180	0.44	0.44
7	23	2.5	1.90	81.2	0.190	0.45	0.43
8	32	10	1.73	69.3	0.160	0.42	0.40
9	23	6	1.75	65.6	0.170	0.44	0.41
10	16	11	1.735	61.9	0.175	0.41	0.40
11	27	6	1.76	62.2	0.165	0.42	0.40
12	23	6.5	1.80	78.8	0.185	0.44	0.40
13	22	2	1.76	72.2	0.160	0.43	0.41
14	19	2	1.73	69.3	0.180	0.40	0.40
15	16	6.5	1.78	81.0	0.175	0.42	0.42
Mean	22.1	5.9	1.77	70.5	0.173	0.424	0.42
S.D.	4.1	3.4	0.05	7.65	0.009	0.014	0.02
Maximum	32	12	1.90	82.2	0.190	0.45	0.44
Minimum	16	2	1.72	58.1	0.160	0.40	0.40

Appendix D

Pilot Study on the Suitability of Using 50 Hz Cameras

Introduction

Selection of an adequate sampling frequency is a prerequisite to any biomechanical study. This is especially true when the movement being investigated is of a rapid ballistic nature, as is the case with Taekwon-Do kicks. It has been suggested that the standard PAL frequency of 50 Hz is insufficient for such movements (Sorenson, 1996). However, the sampling theorem states that "the process signal must be sampled at a frequency at least twice as high as the highest frequency present in the movement itself" (Winter, 1979, pp. 28). Lees (1980) suggested that the filming rate need not exceed 50 Hz for most forms of voluntary human movement (cited in Dainty & Norman, 1987, pp. 80). However, higher rates are required when investigating impacts. Because the movement of interest for the 3D analysis in the present study was the kicking motion until immediately before impact, the proposed sampling frequency of 50 Hz would appear to suffice. A pilot study comparing a 50 Hz analysis to that at a higher frequency was required to validate the use of a 50 Hz sampling frequency to capture and analyse this movement.

Methodology

The fastest part of the kick was determined to be the period just before impact. If this part of the kick, performed by one the fastest subjects, is found to be valid and reliable at 50 Hz, the rest of the movement can be taken to be so also. Because the target area was located just above the hip level of the subject, the leg was presumed to be moving in the horizontal plane during this final phase. Therefore, a Motion Analysis camera sampling at 200 Hz was positioned above the punching bag and subject, facing directly downwards. A one meter square scaling board was videoed, and then two-dimensional video data of the endpoint of the foot for the period before impact with the bag was recorded while the subject performed ten full speed turning kicks.

The scaling board was first digitised and the scaling factor calculated. For each kick captured at 200 Hz, the endpoint of the foot for the fourteen frames before impact was digitised. Raw coordinates were smoothed using a Butterworth digital filter set at an optimal cut-off frequency estimated from the sampling frequency, using an equation proposed by Yu (1988) (described in the kinematic data reduction section). For the 200 Hz data the cut-off frequency was 13 Hz. This filtered data was scaled, and linear velocities calculated using the method of central differences (also described in the section on kinematic data reduction). For comparison with 50 Hz data, all but every forth frame was deleted, and this reduced raw data was filtered by the same method as previously, at a cut-off frequency of 7 Hz. Finally, filtered coordinates were scaled, and linear velocities calculated for the 50 Hz data. To reduce human error, the same scale factor and digitising was used for both trials. For each kick, the linear velocities for the last frame immediately before impact for the two frequencies were compared.

Results and Discussion

The linear velocities for the frame immediately before impact with the bag for each frequency is given in Table D1. The difference between the two is also given. Means and standard deviations are presented below the individual data values.

Table D1

Linear Velocities Between the Last Two Frames Before Impact.

Kick #	Velocity at 200 Hz (m/s)	Velocity at 50 Hz (m/s)	Difference (m/s)
1	12.046	11.665	-0.381
2	12.597	12.300	-0.297
3	12.585	12.177	-0.408
4	13.568	13.344	-0.224
5	12.887	12.716	-0.171
6	14.110	13.959	-0.151
7	14.048	13.591	-0.457
8	13.168	12.898	-0.270
9	13.201	12.949	-0.252
10	13.948	14.045	0.097
Mean	13.216	12.964	-0.271
S.D.	0.782	0.700	0.111

The differences between the two sampling frequencies were all within 0.5 m/s, and the velocities sampled at 50 Hz were consistently smaller than the velocities sampled at 200 Hz by an average of 0.25 m/s. This difference between the means of the two methods of data collection is 1.9% of the first mean, and thus was deemed to be negligible. A Pearson Product-Moment correlation coefficient of 0.98 was computed between the two sets of data. Therefore, the data sampled at 50 Hz can be considered to be representative of that sampled at 200 Hz, and consequently adequate for the present study.

Appendix E

Table E1

Resultant Linear Impulse, Duration of Impact, and Average Impact Force Data for Individual Subjects and the Group.

Subject #	Resultant Linear Impulse (N.s)	Duration of Impact (s)	Average Impact Force (N)
1	45.9	0.12	382
2	37.4	0.12	325
3	29.5	0.10	295
4	18.6	0.09	206
5	22.4	0.08	280
6	40.8	0.12	340
7	35.6	0.11	323
8	35.5	0.12	308
9	21.6	0.12	180
10	32.7	0.14	234
11	37.8	0.12	315
12	23.7	0.08	316
13	27.9	0.11	266
14	40.0	0.15	276
15	33.8	0.10	338
Mean	32.2	0.11	292
S.D.	8.0	0.02	54
Maximum	45.9	0.15	382
Minimum	18.6	0.08	180

Table E2

Linear Velocities of the Joints of the Kicking Leg Immediately Before Impact

Subject #	Toe Vel. (m/s)	Ankle Vel. (m/s)	Knee Vel. (m/s)	Hip Vel (m/s)
1	13.6	12.3	2.34	0.53
2	16.0	13.3	1.51	0.57
3	12.9	11.7	2.42	0.58
4	11.2	10.4	1.70	0.47
5	12.4	12.6	2.70	0.68
6	12.9	11.4	3.30	0.57
7	13.4	12.0	1.42	0.40
8	15.7	13.7	2.56	1.40
9	10.4	10.3	1.67	1.01
10	12.5	10.7	3.09	0.66
11	15.6	14.0	3.31	0.76
12	13.6	12.7	2.13	1.15
13	13.5	12.1	1.57	0.59
14	12.9	12.1	0.20	0.47
15	14.0	12.6	1.66	0.58
Mean	13.4	12.1	2.11	0.69
S.D.	1.6	1.1	0.84	0.28
Maximum	16.0	14.0	3.31	1.40
Minimum	10.4	10.3	0.20	0.40

Table E3

Changes in Angular Velocity at the Ankle and Knee Joints over Phases 1 and 2

Subject #	Δ Angular Vel. at Ankle (degrees/s)		Δ Angular Vel. at Knee (degrees/s)	
	Phase 1	Phase 2	Phase 1	Phase 2
1	-315	475	79	2302
2	- 24	264	129	1958
3	-271	-277	66	1419
4	66	79	98	1515
5	-703	315	386	1818
6	-425	-122	114	1027
7	-565	714	291	1636
8	-224	302	149	1567
9	-411	-60	-113	1148
10	64	12	19	1165
11	-238	153	-161	1366
12	- 82	504	3	1894
13	-192	291	-2	1614
14	-122	93	-26	1692
15	-208	248	-187	1437
Mean	-243	199	56	1570
S.D.	218	258	154	338
Maximum	66	714	386	2302
Minimum	-703	-277	-187	1027

Table E4

Changes in Angular Velocity at the Hip

Subject #	Δ Angular Vel. at Hip_{ele} (degrees/s)		Δ Angular Vel. at Hip_{hor} (degrees/s)	
	Phase 1	Phase 2	Phase 1	Phase 2
1	142	-138	656	-929
2	419	-696	804	-716
3	461	-744	648	-519
4	326	-241	616	-512
5	357	-519	358	-674
6	343	-635	638	-257
7	310	-263	546	-495
8	395	-849	609	-435
9	470	-1100	704	-313
10	569	-717	658	-515
11	543	-931	881	-273
12	684	-512	776	-810
13	202	-260	528	-647
14	304	-497	573	-574
15	591	-683	945	-479
Mean	408	-586	663	-543
S.D.	148	276	147	190
Maximum	684	-138	946	-257
Minimum	142	-1100	358	-959

Appendix F

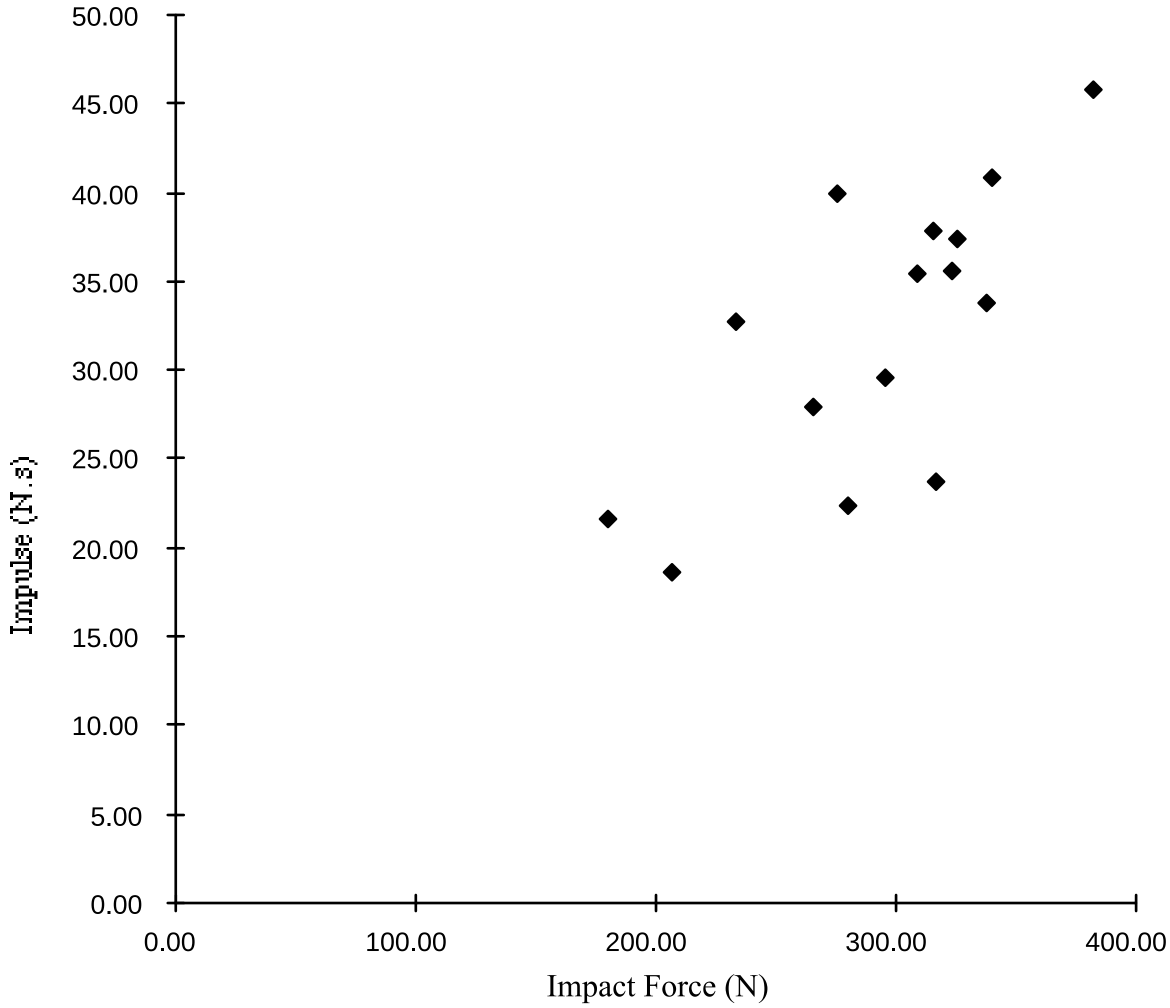


Figure F1. Plot of impulse against impact force

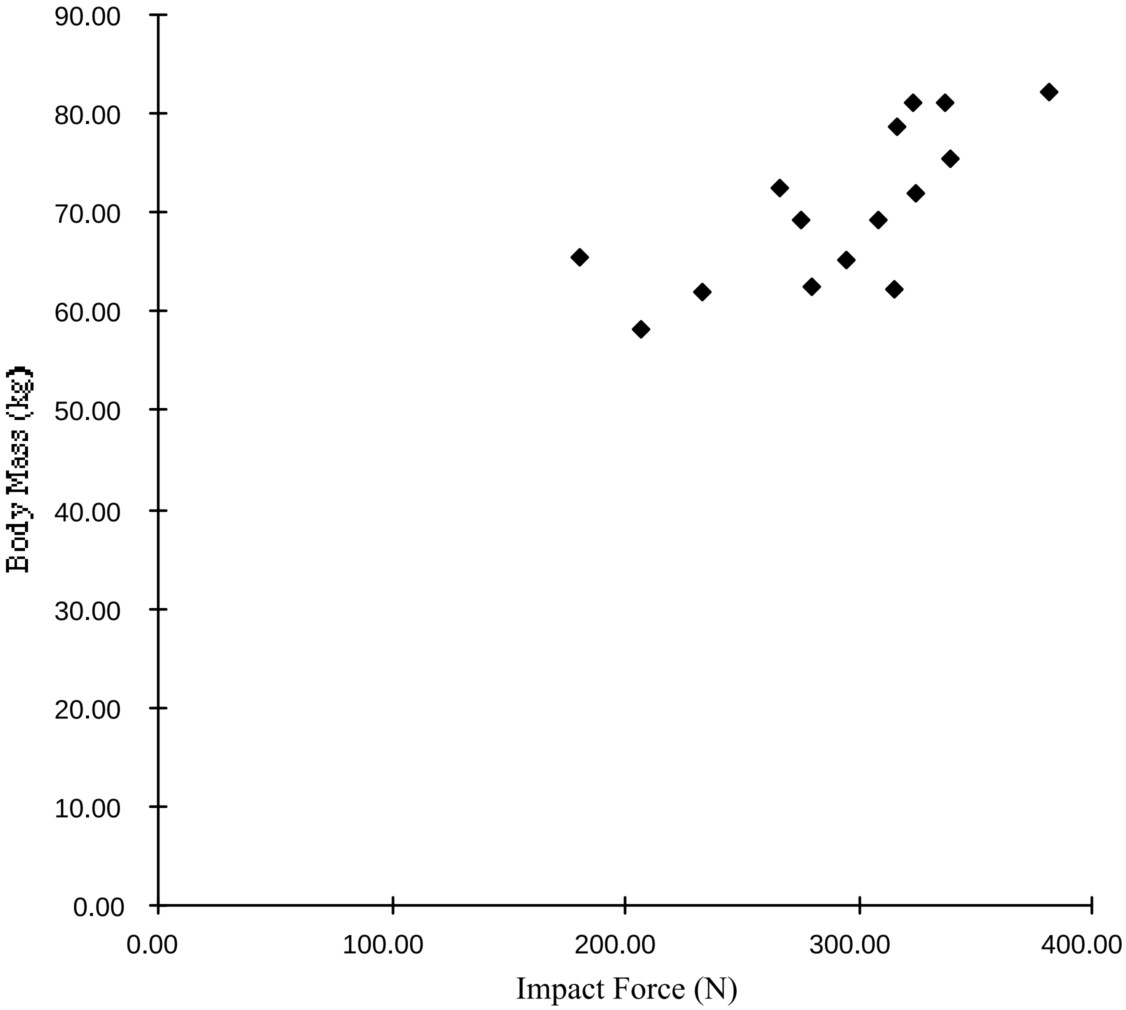
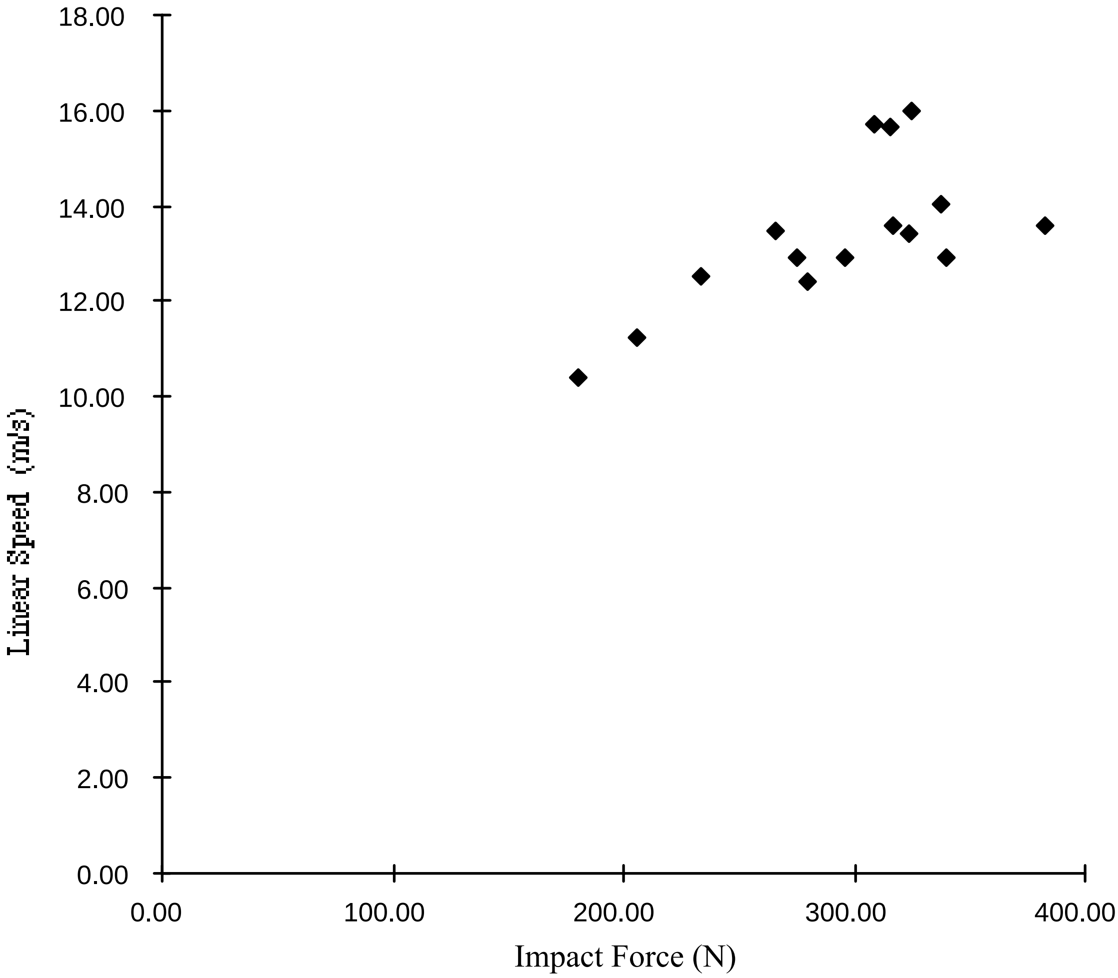


Figure F2. Plot of body mass against impact force



<u>Figure F3.</u> Plot of the linear speed of the toe against impact force

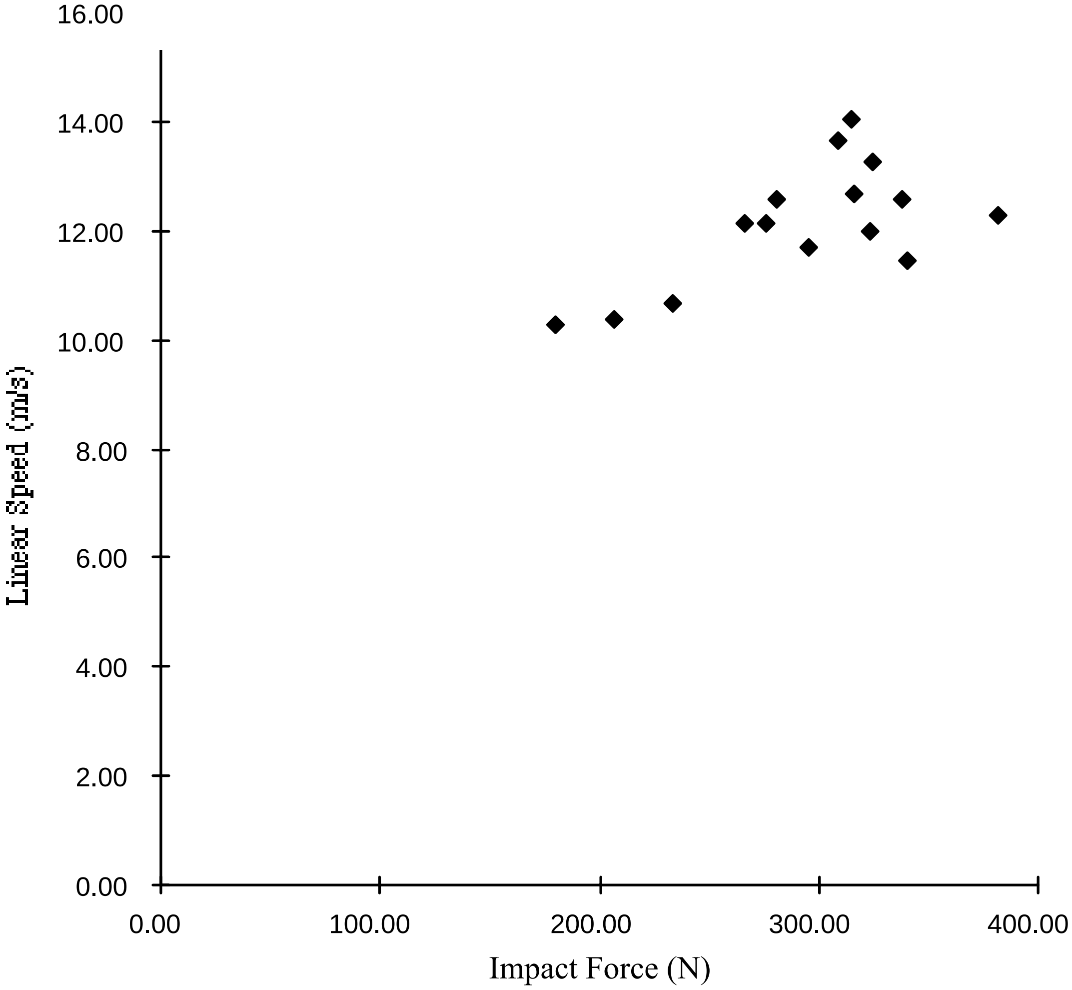
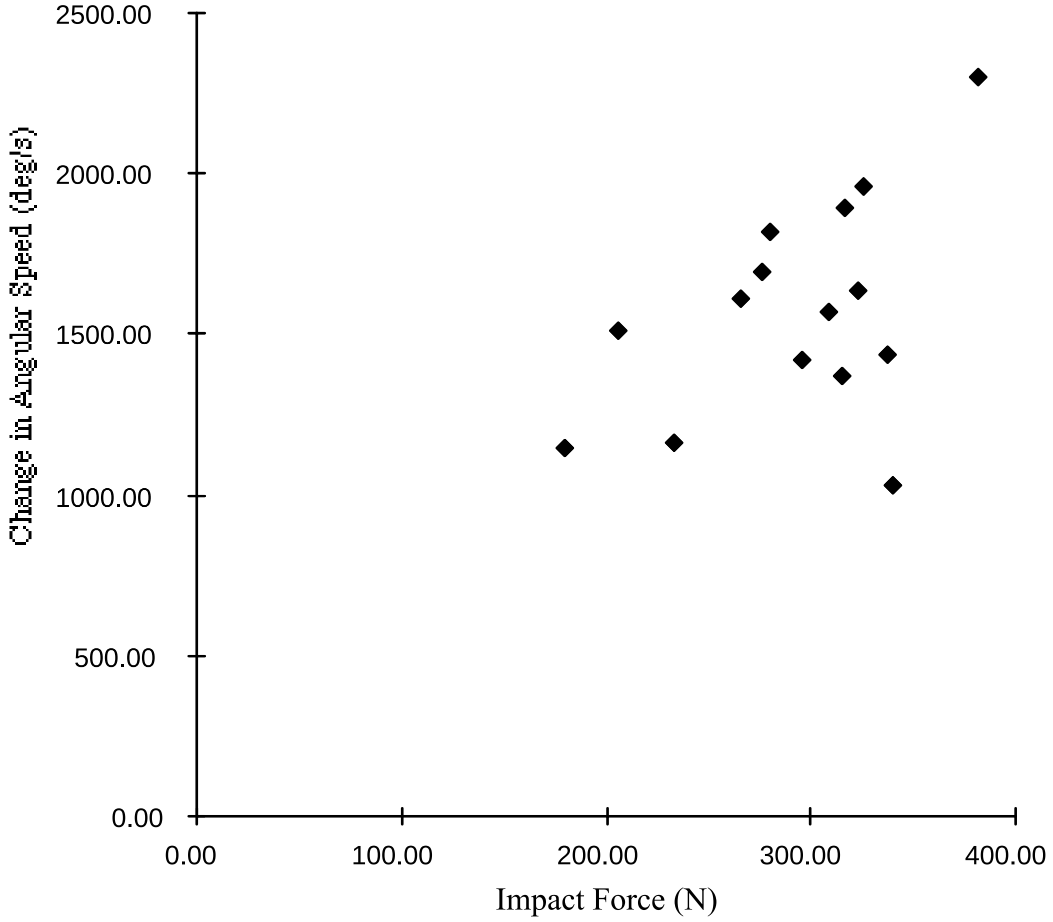


Figure F4. Plot of the linear speed of the ankle against impact force



<u>Figure F5.</u> Plot of the change in angular velocity at the knee during Phase 2 against impact force.

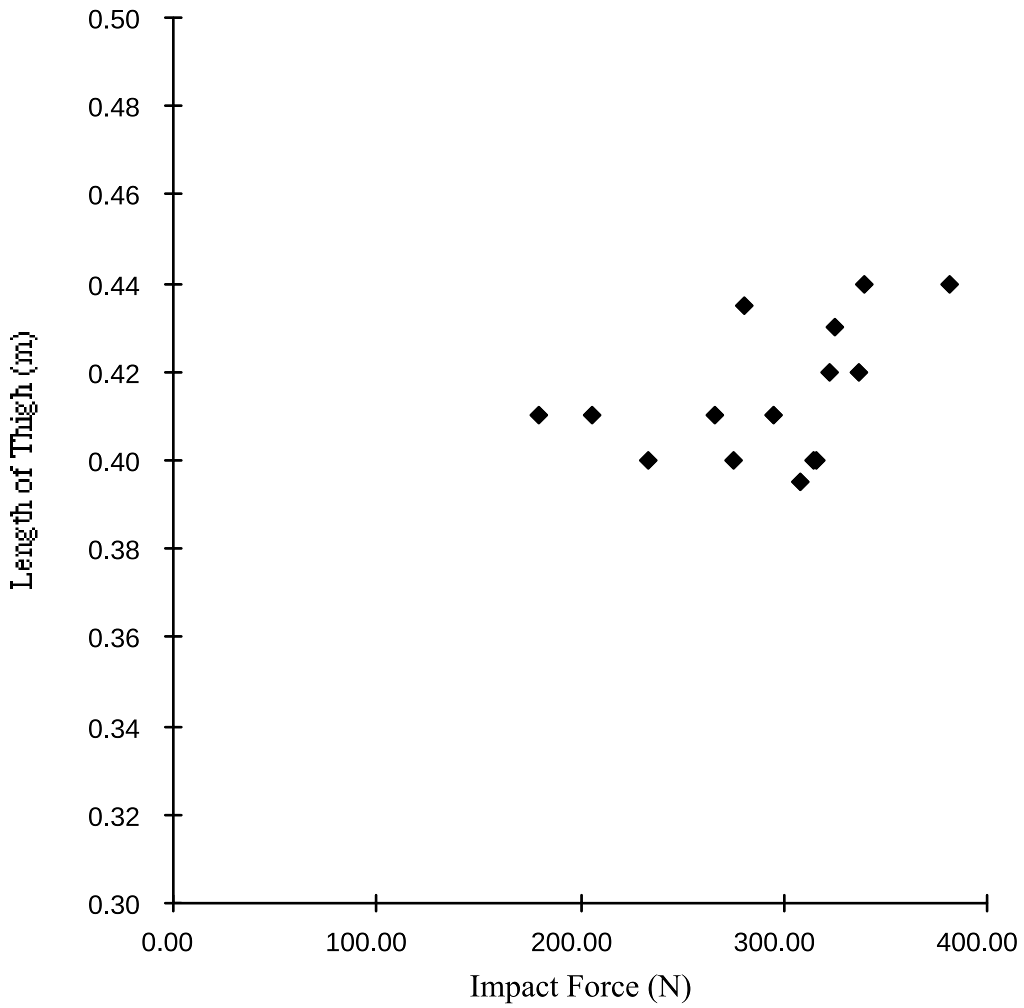


Figure F6. Plot of the length of the thigh against impact force