



**UNIVERSITY OF
TECHNOLOGY SYDNEY**

FACULTY OF BUSINESS

SCHOOL OF LEISURE SPORT AND TOURISM

Biomechanics of the Baseball Swing

Brendan J. Inkster

BA (Human Movement Studies)

This thesis is submitted to fulfil the requirements for the degree Masters by Research
(Sport Studies) at the University of Technology, Sydney, August, 2010.

Certificate of Originality

I certify that the work in this thesis has not been previously submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledge within the text.

I also certify that the thesis has been written solely by me. Any help that I have received in my research work and the preparation of thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of candidate

Production Note:
Signature removed prior to publication.

Acknowledgements

I would first like to thank Dr Aron Murphy for his assistance with the thesis. His knowledge, expertise and support have all helped in the completion of this project. His ability to help turn ok work into great work and constant encouragement is greatly appreciated. Thanks Murf.

I would like to thank Dr Mark Watsford for being my right hand man during the completion of this thesis. Dr Watsford was always willing to answer a question at any time of the day, pertaining to any topic (academic or trivial). Watty will forever be the holder of the key to the sweetest office at UTS.

Next to thanks is Dr Rob Bower, who without his efforts this thesis would not be as technically sound, accurate and methodological. I am very thankful for Rob's expertise in the field of biomechanics and his attention to detail.

I would like to thank my fellow postgraduate students of UTS for making me feel welcome and allowing lunch to be a greatly anticipated event. Special mentions to Daniel Lock and Anthony Witty for their unstoppable humour, sarcasm and support. To Sven Rees for initially showing me the way of how a post-grad should really be

and getting me a job. Thanks also must go to Dr Aaron Coutts for his assistance with the project and invaluable input into lunchtime discussions.

I would like to thank Kanchana Gamage for his technical assistance provided throughout the project, along with his always optimistic attitude (we all know where that dent on the wall came from).

I would like to thank my family for their interest and support throughout the completion of this thesis. Notably, coming in to help with data collection and constantly asking me when exactly the due date was.

I extend thanks to all the participants of the study. Without all the subjects this thesis would never have been possible. Thank you for going out of your way and applying yourselves professionally.

Finally, I would like to thank a very close friend and her family for their encouragement, interest and support during the project. Her thoughts and opinions were always valid and of use within the study. I also thank them for providing another place for me to go outside of university and home.

Dedication

This thesis is dedicated to my parents. They are still the two most knowledgeable people I know and have always been there to support me through my studies.

Abstract

The purpose of this research was to describe the kinematics of the baseball swing. In particular, this study aimed to determine differences in bat swing kinematics in hitters of varying ability. Further, changes in swing pattern that occur when using bats of varying mass were also observed.

Twenty sub-elite male baseballers participated in the study (22.3 ± 5.3 yr, 1.82 ± 0.07 m, 83.5 ± 10.9 kg). Three baseball bats of equal length (0.838m) and varying mass (Bat₁ = 0.795kg, Bat₂ = 0.847kg, Bat₃ = 0.943kg) were used. Each subject performed 10 maximal swings with each bat at a ball on a hitting tee replicating a line drive. Infrared cameras obtained high speed three-dimensional data to quantify the biomechanics during the baseball swing. One-way ANOVA was used to determine kinematic differences between conditions. In addition, the participants were ranked prior to testing based on a novel coach's rating scale and seasonal batting average. They were subsequently separated into a relatively good group of hitters (n=10) and a relatively poor group of hitters (n=10) for comparison. Importantly, the two groups were significantly different in terms of coach's rating ($p < 0.01$) and batting average ($p < 0.05$).

The results showed a significant difference in maximum bat swing velocity ($p < 0.05$) with good hitters having a higher velocity ($36.8 \text{ m}\cdot\text{s}^{-1}$) in comparison to relatively poor hitters ($33.8 \text{ m}\cdot\text{s}^{-1}$). Left elbow maximum angular velocity was significantly higher (35.9%) amongst relatively good hitters ($p < 0.05$). Good hitters also had a right knee angle of 106° at ball contact which was significantly ($p < 0.05$) higher than relatively poor hitters (100°). There were no between-group differences for wrist and hip joint velocities at ball contact.

The results also showed a difference in maximum bat swing velocity ($p < 0.01$) between Bat₁ ($36.0 \text{ m}\cdot\text{s}^{-1}$) and Bat₃ ($34.4 \text{ m}\cdot\text{s}^{-1}$). Resultant ball velocity was 17% higher using Bat₁ compared to Bat₃ ($p < 0.05$). Subject head movement was lower using Bat₁ (8 cm) when compared to Bat₃ (10 cm). Maximum linear left hip velocity was significantly higher ($p < 0.01$) when using Bat₃ compared to other bats. In contrast, maximum linear right hip velocity was lower ($p < 0.01$) when using Bat₃.

This study established that bat swing velocity is a key characteristic of the baseball swing when identifying skill level and performance between hitters. Additionally, good hitters display greater lead elbow maximum angular velocity. Future research should develop and evaluate specific baseball training programs designed primarily to improve these two aspects of the baseball swing. Further, this study has identified aspects of the baseball swing that differ when using bats of varying mass. Notably, a relationship exists between bat mass and hip linear velocity which could be a

potential mechanism for underlying training effects. Further studies are needed to determine acute and longitudinal kinematic effects of using bats of varying mass.

Table of contents

Certificate of Originality	ii
Acknowledgements.....	iii
Dedication	v
Abstract.....	vi
Table of contents	ix
List of Tables	xii
List of Figures.....	xiv
List of Equations	xv
List of Abbreviations	xvi
List of Publications.....	xviii
CHAPTER 1 - INTRODUCTION	1
1.1 Background.....	2
1.2 Statement of the Problem	6
1.3 Research Hypothesis	7
1.4 Purpose and Significance of the Project.....	7
1.5 Limitations	9
1.6 Delimitations.....	9

CHAPTER 2 - REVIEW OF LITERATURE	10
2.1 Overview	11
2.2 The Game of Baseball.....	11
2.3 Biomechanics of Baseball Batting.....	15
2.3.1 Biomechanics of the Baseball Swing	15
2.3.1.1 Preparation.....	19
2.3.1.2 Initiation.....	19
2.3.1.3 Load	20
2.3.1.4 Shift and Transfer	20
2.3.1.5 Contact.....	22
2.3.1.6 Summary.....	23
2.4 Characteristics of the Baseball Bat.....	24
2.4.1 Mass and Length	27
2.4.2 Moment of Inertia.....	27
2.4.3 Coefficient of Restitution.....	30
2.4.4 Aluminium vs. Wood	31
2.5 Bat Swing Velocity	32
2.5.1 Acute Methods for Improving Bat Swing Velocity	33
2.5.2 Training Methods for Improving Bat Swing Velocity	36
2.6 Summary.....	41
CHAPTER 3 - METHODS	43
3.1 Overview	44
3.2 Participants.....	44
3.3 Testing Procedures.....	46
3.4 Data Collection	49
3.5 Data Processing	51
3.6 Data Analysis	53

CHAPTER 4 - RESULTS	55
4.1 Overview	56
4.2 Relatively Good vs. Relatively Poor Hitters.....	56
4.3 Correlations between bat swing kinematics.....	60
4.4 Manipulating Bat Mass.....	62
4.5 Summary of Key Results	66
CHAPTER 5 - DISCUSSION	68
5.1 Overview	69
5.2 Relatively Good vs. Relatively Poor Hitters	70
5.3 Manipulating Bat Mass	74
5.4 Summary.....	78
CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS	79
6.1 Overview	80
6.2 Summary of Major Findings and Conclusions.....	80
6.3 Directions for future research.....	82
REFERENCE LIST	85
APPENDICES	95

List of Tables

Table 2.1 – Elite Hitter’s Swing Characteristics	18
Table 2.2 – Bat Velocity after warm-up with bats of varying mass (adapted from De Renne et al. (1992, p. 216))	35
Table 2.3 – Group mean bat swing velocities and percent change (Sergo & Boatwright, 1993)	39
Table 2.4 – Training Schedule (DeRenne et al., 1995, pp. 248)	40
Table 2.5 – Group mean bat swing velocities and percent change (DeRenne et al., 1995)	41
Table 3.1 – Biomechanical variables calculated for the bat swing	52
Table 4.1 – Kinanthropometric data for each group (mean \pm SD)	57
Table 4.2 – Results for all participants and comparative data for the good group and poor group for bat swing kinematics (mean \pm SD)	58
Table 4.3 – Upper body bat swing kinematics (mean \pm SD)	58
Table 4.4 – Lower body bat swing kinematics (mean \pm SD)	59
Table 4.5 – Pearson’s correlation data for the relationship between bat and ball variables (A = Maximum Bat Linear Velocity, B = Bat Linear Velocity at Contact, C = Maximum Ball Linear Velocity)	61

Table 4.6 – Pearson’s correlation data for left elbow kinematics	61
Table 4.7 – Pearson’s correlation data for hip kinematics	62
Table 4.8 – Kinematic comparisons between bats of different mass. Data is mean \pm SD	65

List of Figures

Figure 2.1 – Participation Rates in Baseball and Cricket – 2009 (ASC, 2009)	14
Figure 2.2 – Phases of the Swing	17
Figure 2.3 – Theoretical effects of increased bat swing velocity. Assuming a pitched ball speed of $40\text{m}\cdot\text{s}^{-1}$, a take off angle of 35 degrees, and neglecting wind and air resistance	33
Figure 3.1 – Marker Placement on the Subject	47
Figure 3.2 – Baseball Bats	49
Figure 3.3 – Camera set-up surrounding batting tee and hitting net	51
Figure 4.1 – Bat swing velocities (+ SD) and resultant ball velocity (+ SD) between bats	63
Figure 4.2 – Left and right hip velocities (+ SD) for each bat	64

List of Equations

Equation 1 – Rotational Inertia 27

$$I = (1/4)MR^2 + (1/12)ML^2$$

Equation 2 – Moment of Inertia 28

$$I_o = \frac{T^2 \bullet w \bullet r}{4\pi^2}$$

Equation 3 – Radius of Gyration 28

$$k = \sqrt{\frac{I_o}{m}}$$

Equation 4 – Centre of Percussion 29

$$q = \frac{k^2}{r}$$

Equation 5 – Coefficient of Restitution 30

$$e_o = -\frac{v'-V'}{v-V}$$

List of Abbreviations

3D	Three Dimensional
ANOVA	Analysis of Variance
BP	Batting Practice Group
BSV	Bat Swing Velocity
BSV_{con}	Bat Swing Velocity at Contact
BSV_{max}	Maximum Bat Swing Velocity
BV_{max}	Maximum Resultant Ball Velocity
CG	Control Group
COP	Centre of Percussion
COR	Coefficient of Restitution
°	Degrees
°·s⁻¹	Degrees per second
DS	Dry Swing Group
Hz	Hertz
ICC	Interclass Correlation
in	Inches
kg	Kilograms
KP	Kilopond
LEAV_{max}	Maximum Left Elbow Angular Velocity
m	Metres
m·s⁻¹	Metres per second
MLB	Major League Baseball

MOI	Moment of Inertia
NCAA	National Collegiate Athletic Association
NSWML	New South Wales Major League
oz	Ounces
RPM	Revolutions per minute
SD	Standard Deviation
SPSS	Statistical Package for the Social Sciences
TEM	Technical Error of Measurement
USA	United States of America
WBC	World Baseball Classic
yrs	Years

List of Publications

Inkster, B., Murphy, A., Bower, R. & Watsford, M. Differences in the kinematics of the baseball swing between hitters of varying skill. (In Press: *Medicine and Science in Sports and Exercise*).

Conference Proceedings

Inkster, B. J., Murphy, A. J., Bower, R. & Watsford, M. L. (2010). Differences in the kinematics of the baseball swing between bats of varying mass. *Exercise and Sports Science Australia Conference*. Gold Coast, Australia. April 9-11.

Inkster, B. J., Murphy, A. J., Bower, R. & Watsford, M. L. (2009). Differences in the kinematics of the baseball swing between hitters of varying skill. *Australian Conference of Science & Medicine in Sport*. Brisbane, Australia. October 14-17.

CHAPTER 1

INTRODUCTION

1.1 Background

Baseball is a sport that attracts significant interest around the world. It has become a multi-million dollar business not only in the United States of America (USA), but in countries such as Japan and Korea. Batting is a crucial facet of the sport and improving batting performance has been a primary concern of coaches and players for many years. Despite this, there has been relatively little research on the biomechanics of the baseball swing. Specifically, bat swing velocity has been identified as a key determinant of a batter's performance (Breen 1967; Lund & Heefner 2005). Accordingly the mass of the bat is often manipulated either during games, warm-ups and/or training to improve or facilitate bat swing velocity. The significance of increased bat velocity is that it potentially increases decision time for the batter (i.e. the time they have to decide to hit the ball) (Szymanski 1998). Furthermore it increases the force that can be transferred to the ball allowing it travel further (Lund & Heefner 2005). Increasing bat velocity also increases the bat's momentum, momentum transfer and batted ball velocity (Fleisig et al. 2002). Thus, there is a high importance in determining the key swing characteristics that lead to a successful baseball swing and how bat mass may affect bat swing kinematics.

Biomechanics of Hitting

The skill of hitting a baseball can be broken down into a number of phases to facilitate analysis: preparation; initiation; load; shift and transfer; and contact (Russo

& Landolphi 1998). Research by Welch et al. (1995) gave a biomechanical description of the swing and presented it in similar phases, providing a detailed analysis of the swing using minor league baseball players as subjects. This research showed that the swing was initiated with a weight shift toward the back leg and that maximum hip rotation occurs approximately 0.35 s before contact. Linear maximum velocity of the bat occurred 0.015 s before bat/ball contact, simultaneously with a right arm maximum extension velocity of 948°s^{-1} .

Sawicki et al. (2003) examined factors that influence the range of the ball. The authors reported that resultant distance travelled by the ball is most sensitive to bat velocity and not to wrist roll. Recent research by Tabuchi, Matsuo & Hashizume (2007) supported the findings of Sawicki et al. (2003), showing that it is desirable for elite hitters to impact the ball when the bat head is at its lowest point during the swing and more importantly, at peak bat swing velocity. The implications are that bat velocity is a particularly important component and should take priority in hitting training.

To achieve increased bat swing velocity, the majority of power must come from the large musculature of the legs and trunk rather than the hands and wrists. However, the power of the swing can only be generated when the batter creates energy in the early stages of the swing and shifts that energy to the bat during the later phases of the swing (Adair 1995). Energy is transferred sequentially from the legs to the trunk, shoulders, arms and hands, and concludes with energy transferred to the baseball bat. High speed video has shown that efficient batters are almost motionless at ball

contact as all the stored energy has been transferred through the arms and into the bat (Adair 1995).

The baseball swing has many performance characteristics that players need to achieve during each phase to be successful (Cluck 1993; Russo & Landolphi 1998). Elite hitters show various, yet effective swing traits, however they still share common technique points (Breen 1967). It is still unknown as to whether non-elite players exhibit similar or different characteristics of elite players. Through an effective analysis of the swing pattern, these performance characteristics can be identified and models of elite performance may be developed. Such analysis would certainly assist baseball coaches, conditioning coaches and sport scientists in training baseball hitters.

Manipulating Bat Mass

A hitter's role within a team varies and so does their chosen bat. The main variables when choosing a bat are its mass, its length and its moment of inertia (how the mass is distributed). The standard mass and length of baseball bats, for sub-elite baseballers, ranges from 0.822 to 0.878 kg (DeRenne et al. 1995; DeRenne et al. 1992; Hughes, Lyons & Mayo 2004; Otsuji, Abe & Kinoshita 2002; Sergio & Boatwright 1993; Szymanski et al. 2006) and from 0.812 to 0.863 m (Hughes, Lyons & Mayo 2004; Otsuji, Abe & Kinoshita 2002; Southard & Groomer 2003; Szymanski et al. 2006) respectively. The mass of a baseball bat is often modified for

game use, training programs and warm-up procedures, with the intent of improving performance (Southard & Groomer 2003). However, many misconceptions have arisen regarding the effect of bat mass on swing kinematics and bat swing velocity (such as swinging two bats at once in warm-up, with the intent of increasing bat swing velocity during performance). Furthermore, there is a paucity of research examining changes in swing biomechanics when using bats of varying mass.

Although training methods vary amongst studies (DeRenne et al. 1995; Sergio & Boatwright 1993), research has generally agreed that training with a weighted baseball bat can improve bat swing velocity. Sergio & Boatwright (1993) recorded an 8% increase in (game) bat swing velocity using a 1.757 kg bat in training (double the mass of a regulation game bat). Whereas DeRenne et al. (1995) found an increase of 9% using a combination of bats in training, ranging from 0.765 to 0.964 kg.

Finding the correct mass to use in a training study and during warm-ups is critical as overloading the implement can potentially have an adverse effect on bat velocity and technique. A reduction in maximum bat swing velocity has been demonstrated when warming-up with bats greater or less than 12% of original bat weight (DeRenne et al. 1992). In addition, the research by DeRenne et al. (1992) used a light timing device to record bat swing velocity, ignoring baseball swing biomechanics. As such, the mechanisms by which changes in bat swing velocity occurred remain unknown. Moreover, it is important to recognise such mechanisms so that training can be specific and be better served in improving bat swing velocity.

Southard & Grommer (2003) changed the mass of a baseball bat (increased the bat's moment of inertia) during warm-up and examined the subsequent effects on the biomechanics of the swing. Warming-up with a heavier bat significantly reduced bat swing velocity by 20% and affected swing patterns by significantly slowing lead wrist velocity and increasing lead elbow velocity (Southard & Grommer 2003). Moment of inertia was increased by adding weight to a standard bat, however the researchers only examined the acute effects on bat swing biomechanics. Thus, the need for further analysis of baseball bat swing biomechanics is necessary as it may distinguish possible relationships between bat swing velocity and biomechanical deficiencies.

1.2 Statement of the Problem

Research has demonstrated that bat swing velocity is a key determinant of batting performance in elite baseballers (Breen 1967). Some studies have reported that weighted implement training programs utilising bats of varying mass will increase bat swing velocity, by up to 10%. However, the mechanism by which such improvements occur remains unclear. In addition, there is an absence of literature examining the biomechanics of the swing when using bats of different mass. Furthermore, there has been a limited amount of research conducted in this area, and thus the key kinematic differences between good and poor level hitters also remain unknown.

This project aimed to:

1. Provide a detailed analysis of the kinematics of the baseball swing;
2. Identify the kinematic differences between hitters of relatively good and relatively poor ability, and;
3. Determine the specific kinematic differences that occur when swinging bats of different mass.

1.3 Research Hypothesis

It was hypothesized that:

1. There would be differences in swing kinematics between hitters of relatively good and relatively poor ability.
2. There would be no changes in the kinematics of baseball bat swing technique when using bats of various mass.

1.4 Purpose and Significance of the Project

The purpose of this project was to investigate the biomechanics of the baseball swing and the effects of differently weighted bats on baseball bat swing biomechanics in sub-elite baseballers. Furthermore, the study aimed to discover any kinematic changes displayed between hitters of varying ability and help to identify factors that

significantly affect hitting performance. In addition, the determination of specific characteristics that differentiate between good and poor hitters will help to improve training prescription, as coaches will have an improved knowledge of the areas of the swing to focus more time and effort towards.

When considering the practical applications of the study, some previous research has not included the use of a ball during the analysis of the baseball swing. Such methodology may not accurately reflect the actual movement patterns performed during baseball match-play. The methodology used in this study incorporated a more realistic swing pattern as the participants were required to contact a ball during the swing phase.

In addition to the direct application of the findings to baseball batting performance, the examination of the specific swing kinematics in the current study may also be of interest to conditioning coaches from other sports involving ball striking such as hockey, cricket and tennis.

1.5 Limitations

The current study was limited by:

1. The trials were conducted under controlled laboratory conditions and were therefore not directly applicable to field situations where factors such as game situation, pitched ball velocity, ball rotation, and wind speed may affect results;
2. It was assumed that participants gave their maximal effort in all trials.

1.6 Delimitations

The following delimitations were set in the current study:

1. Sample size;
2. The present study was conducted using sub-elite male baseballers; therefore the study was delimited to this demographic;
3. The use of only 4 infrared motion analysis cameras;
4. The choice of the marker set used;
5. A hitting tee was used to position the ball prior to the subject's swings.
6. Only 3 bat masses were used in the current study.

CHAPTER 2

***REVIEW OF
LITERATURE***

2.1 Overview

This review will critique literature on baseball bat swing biomechanics with particular reference to (a) the key variables underpinning batting performance, (b) the differences in technique and biomechanics between elite and sub-elite hitters (c) the acute effects of using bats of different mass, (d) adaptations observed as a result of training with bats of varying mass and (e) the influence these adaptations have on performance. The review begins with a brief history of baseball, specifically Australian baseball, and how Australian baseball fits into the world sporting spectrum, followed by an examination of the significance of batting in the game of baseball. Baseball bat swing biomechanics will then be reviewed and characteristics that elicit successful performance will be highlighted, in both elite and sub-elite performers. Following this, the review of literature will focus briefly on training and warm-up methods to improve batting performance. Specifically, the literature surrounding the relationship between manipulating bat mass, change in biomechanics, and performance will be discussed. Throughout the review, specific attention will be paid to baseball bat swing velocity due to its apparent importance in maximising performance.

2.2 The Game of Baseball

Baseball, or a form of, has been around for over 200 years, which makes it much older than other modern day sports. Its origins were derived from many games including rounders, stick ball, base, and goal ball. The first baseball game is documented to have been played in 1845 in New York, USA (Clark 1993). It wasn't until the late 1860's that baseball became America's national pastime, by this time baseball had already been seen and played by Australians. In 1857, American's played the first game of baseball in Melbourne, Australia.

Australian's took to the sport in 1867, with the first game played prior to an Australian football match (Clark 1993). By the early 1900's, the sport had developed, many clubs had been formed, an Australian tour had taken place by Americans, and the playing of the first National Championships in 1899 occurred. Throughout the 1920's the game grew in popularity within America with the introduction of baseball greats such as Herman 'Babe' Ruth and Lou Gehrig. Baseball was unquestionably the biggest team sport in America during this period. It was the hitting capabilities of these players that enticed audiences to the stadiums and kept fans coming back for more.

With the emergence of other sports in modern society, today's game holds less presence within the world sporting arena and there is less 'hype' over baseball than there was in the first half of the 20th century. Baseball is now ranked 4th in popularity in America behind professional football, college football and professional basketball (Lerner & Lerner 2007). Much of baseball's decline in popularity was a result of an increase in external factors such as sponsors, salaries, racism, and drug taking, all of which have caused turmoil in the sport since the late 1950's. Although the game itself is now much faster, more powerful, and more exciting to play and watch, it is these factors that have attributed to baseball's downfall. In recent decades baseball has experienced much change, resulting in a game that is growing in popularity in Australia (28% increase in participation rates between 2002-2009 (Australian Sports Commission 2002, 2009)), but still has room to be developed.

In recent times world baseball has been dominated by North and South American teams, along with many Asian nations including Japan and Korea. Australian teams have performed well in the last decade, comprised of mixed results, most significantly a silver medal at the 2004 Summer Olympics. In 2006, the inaugural World Baseball Classic took place and baseball witnessed a true world class competition with almost all professional players being available to play. However, Australia placed last in its pool, ranking them 13th to 16th in the

world. More recently at the 2009 World Baseball Classic, Australia once again could not get past the pool stage but were ranked 9th to 12th overall, with Japan beating Korea in the championship game. Later in 2009, Australia placed 5th in the baseball world cup (their best ever result) which has them currently ranked 11th in world baseball (International Baseball Federation 2010).

In 2006, there was over 300 Latino's (29.4%) playing MLB (Lapchick, Ekiyor & Ruiz 2006) and just nine Australians (<1%). Thus, the likely success of a national team reflects heavily on the participation rates of that sport in its country and in MLB. Baseball's biggest competitor for participation in Australia is cricket as they are both predominantly summer sports (See Figure 2.1 for a comparison of participation rates between baseball and cricket). Potential participants for baseball have been lost due to the loss of a professional league and the sub-standard performance of Australian baseball teams, which has also lead to greater attention being paid to cricket (and its success). According to the 2009 Participation in Exercise, Recreation and Sport Survey (Australian Sports Commission 2009), 46,700 adults were participating in baseball in Australia. Of these 75% were male, with 18,200 participating in New South Wales (Figure 2.1).

Baseball vs. Cricket Participation - 2009

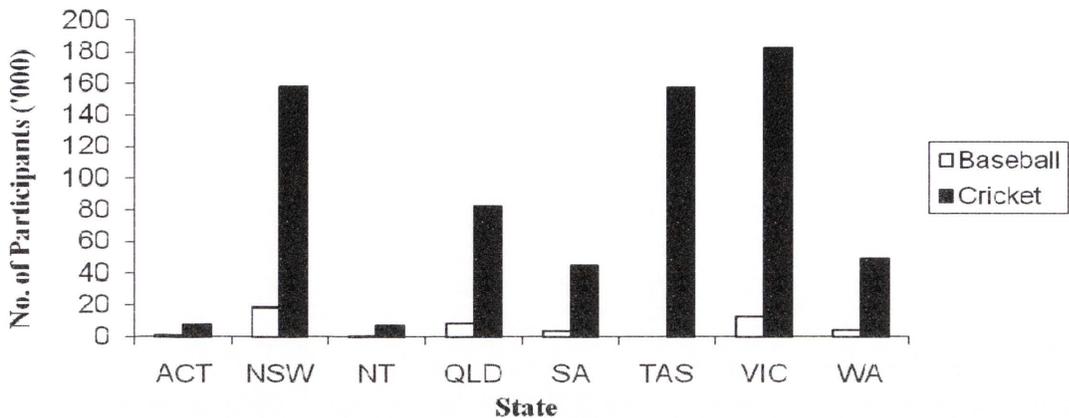


Figure 2.1 – Participation Rates in Baseball and Cricket – 2009 (ASC, 2009)

Australian baseball has produced, and is producing, quality top level professional players. There are over 90 players in the minor league and major league systems in the USA, along with over 60 attending colleges across America. Most of the professional players are in the minor leagues, however 26 Australians have played MLB, and of those, 10 are still active. Of these 26, 17 are pitchers, highlighting the fact that Australians are weaker in the areas of hitting and fielding compared to others in the MLB.

Hitting a baseball is arguably the most exciting part of the game. The evolution of the baseball swing and the baseball batter (Breen 1967; Welch et al. 1995) has seen a remarkable change to the game, which could lead to greater audience size and a much faster and powerful game.

2.3 Biomechanics of Baseball Batting

The object of hitting a baseball varies according to game situation. In general, batters try to achieve a safe hit within the playing boundaries. Other types of shots include sacrifice flies (where the batter tries to hit a long fly ball to the outfield), bunts (the batter keeps the bat motionless and lets the ball hit the bat), and slap hits (the main objective of the batter is to make some form of contact with the ball). Classifications of hitters are derived from the type of shot they are most likely to perform in a game. The most common hitters are: the power hitter (batters who drive the ball, often hitting home runs and other extra-base hits); the slap hitter (batters who simply try to "slap" the ball through the infield to reach base); and, the complete hitter (batters who can slap the ball if required, but can come up with extra base hits). Each type of hitter will possess certain performance characteristics (Breen 1967) essential to their style of hitting, often overlapping.

2.3.1 Biomechanics of the Baseball Swing

Hitting a baseball involves a series of inter-linked movements. The result of these movements is a sequential generation of power that is then transferred to the bat (generically termed the kinetic link principle). The kinetic link can be briefly described as the transfer of angular momentum through the sequential acceleration and deceleration of body segments (Putnam 1993), with the following characteristics; 1) the system of links has a base (fixed end) and a free (open end); 2) the largest segments are most proximal and the smallest segments are most distal; and 3) an external torque is applied to the base segments to initiate the system's motion and give the entire system angular momentum.

The skill of hitting a baseball can be broken down into a number of phases to allow for analysis. Russo & Landolphi (1998) used the following five phases: preparation; initiation; load; shift and transfer; and contact (Figure 2.2). A study by Welch et al. (1995) gave a biomechanical description of the swing and presented it in similar phases (foot off/stride, foot contact, and ball contact), disregarding the preparation and initiation phases. This study provided a detailed analysis of the swing, however due to a lack of research examining a variety of baseball populations, it is difficult to draw conclusions as to the difference in technique between good and poor hitters. In addition, it should be noted that two of the predominant biomechanical analysis of the baseball swing (Breen 1967; Race 1961) are from over 30 years ago and as such there have since been advancements in data collection and data analysis procedures. Despite the absence of research, key performance variables can be observed during each phase of the swing that allow the sports scientist to distinguish between elite and sub-elite performers. Extrinsic factors, such as the characteristics of the bat, may also be considered alongside intrinsic factors (hitting biomechanics) when analysing final performance, such as batted ball velocity.

The baseball swing has many essential characteristics for successful execution (Cluck 1993; Russo & Landolphi 1998). Although elite hitters show various, yet effective swing traits (Table 2.1) they still share common technique points (Breen 1967). Through an effective analysis of the swing pattern, these performance characteristics are identified and models of elite performance may be developed.

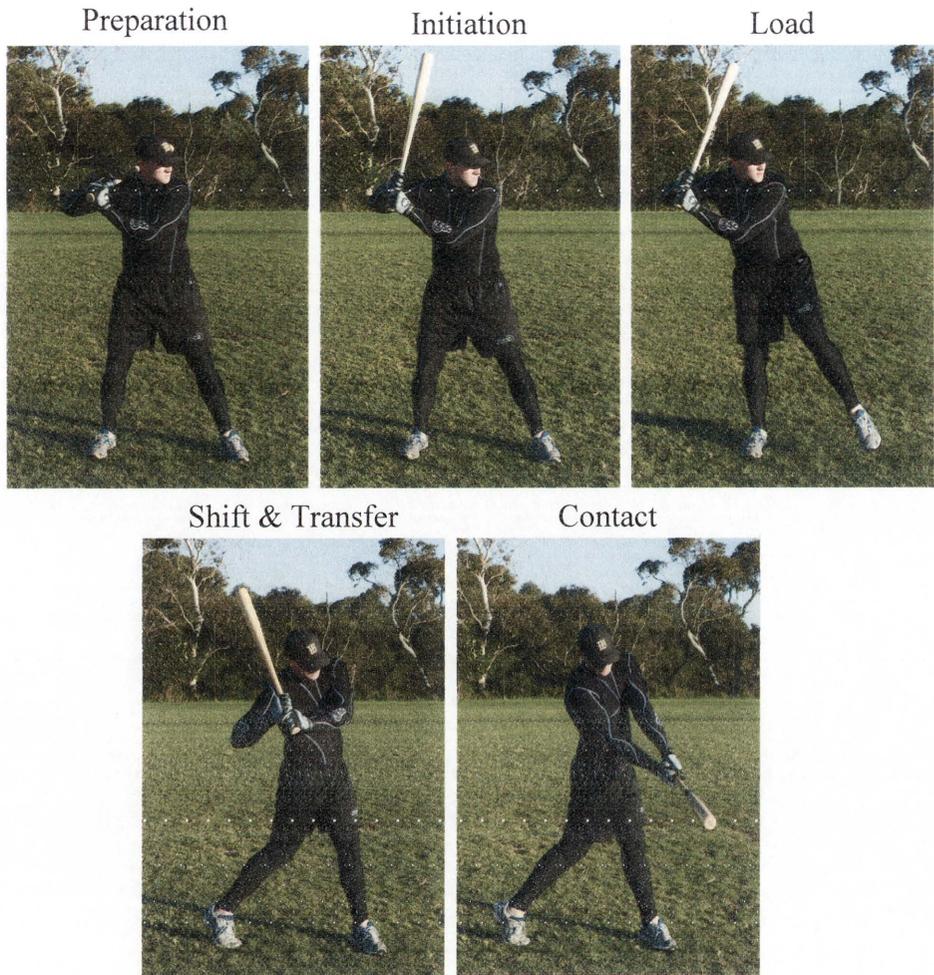


Figure 2.2 – Phases of the Swing

Table 2.1 Elite Hitter’s Swing Characteristics

Author	Participants	Research Methods	Characteristics	Effect on Swing
(Race 1961)	Major League Baseballers	High Speed Video (50Hz)	<ul style="list-style-type: none"> • Hip Rotation • Quick and powerful wrist action • Bodily balance 	<ul style="list-style-type: none"> • Transfer greater momentum to upper body • Apply final summation of force to the bat • Keeps head (eyes) level
(Breen 1967)	Major League Baseballers	Cinematography	<ul style="list-style-type: none"> • Centre of gravity stays level • Head is able to adjust from pitch to pitch • Leading forearm straightens immediately at beginning of swing • Stride length is consistent on all pitches • After contact, upper body position is in the same direction as the ball 	<ul style="list-style-type: none"> • Keeps head (eyes) level • Increase ability to see pitch for longer • Leads to increased bat swing velocity • Essential for effective transfer of momentum • Reflection of proper utilisation of the kinetic link principle
(Welch et al. 1995)	Minor League Baseballers	Motion Capture Software (200Hz)	<ul style="list-style-type: none"> • Proper timing – this allows for higher rotational velocities 	<ul style="list-style-type: none"> • Leads to increased bat swing velocity, as summation of forces is most efficient

Note: The following technical description of the baseball swing is for a right handed hitter.

2.3.1.1 Preparation

The hitter chooses a comfortable grip and steps into the batter's box and assumes their stance (Russo & Landolphi 1998). They then focus their eyes on the pitcher who is approximately 18.5 m away, as the pitcher starts moving towards the plate the eyes focus on the pitcher's release point. The eyes then pick up the ball at the release point and the tracking process begins. To get the best and longest possible look at the flight of the ball a good hitter should be able to adjust his head from pitch to pitch (Breen 1967), a process that begins during pitch tracking.

2.3.1.2 Initiation

The swing is initiated with a weight shift (different for each individual) toward the right leg (back leg) (Welch et al. 1995). At approximately the same time, the upper body rotates in a clockwise direction around the axis of the trunk, initiated by the arms and shoulders, and followed closely by the hips. Cluck (1993) suggests that rotation of the hips is a key performance characteristic for the development of a powerful swing, as it allows for a greater transfer of momentum to the upper body. However, no research has examined how much momentum is transferred between the segments and whether relative differences occur between good and poor hitters.

2.3.1.3 Load

Following the initiation of the swing, the left leg lifts and the left foot brakes contact with the ground, increasing total force applied to the right foot (Welch et al. 1995). The left foot then begins to stride forward. As the front foot strides towards the pitcher, better hitters can keep their hands back for longer (Cluck 1993), as they have a faster bat swing. It is also important in this phase to ensure that the hands get into a hitting position (area just below the shoulders, with lead elbow at 90 degrees flexion), as this will allow for greater contact and power (Cluck 1993).

2.3.1.4 Shift and Transfer

As the stride continues to foot down, the hips reach maximum clockwise rotation, approximately 350 ms prior to ball contact (Welch et al. 1995). It is critical that the timing of the stride (foot contact) is correct, so it can act as a trigger for the bat swing (Russo & Landolphi 1998). At this instance, the hips begin to rotate in a counter-clockwise direction. Uncoiling of the hips generates power (Cluck 1993), which begins the transfer of momentum to the bat. The shoulders, however, continue in a clockwise direction, increasing the coil of the trunk until they reach a maximum rotation, ~265 ms prior to ball contact (Welch et al. 1995). At that instant, they change direction and follow the lead of the hips in a counter-clockwise rotation towards the ball. The arms, at the same time, continue in a clockwise rotation around the axis of the trunk, increasing the coil of the upper body against movement of the hips and shoulders.

As the left forefoot makes contact with the ground, the length and direction of the stride are defined. The front foot stride length needs to be appropriate so that it doesn't cause a 'lock' of the hips (Cluck 1993) and elite hitters generally have the same stride length on all pitches (Breen 1967). However stride length is individually determined and thus is different between hitters. It is with the left foot contact that the hitting action becomes a closed chain energy transfer. The arms which increase the coil of the upper body by continuing in a clockwise rotation around the axis of the trunk reach a maximum position and begin a counter-clockwise rotation (Welch et al. 1995). In order to achieve maximum bat velocity and maximise efficient contact it is important also that the hitter uses an inside-out swing, whereby the hands are ahead of the bat-head at ball contact (Cluck 1993).

A batter's weight shifts forward as the heel of the left foot makes contact with the ground. With the weight shifted forward, segments now accelerate to maximum velocities as the body coordinates an effort to produce maximum bat speed. The left leg extends at the knee, pushing the left hip backwards, while the right leg pushes the right hip forward, creating a counter-clockwise acceleration of the hips around the axis of the trunk. The rotational velocity of the hips increases to maximum, ~75 ms prior to ball contact (Welch et al. 1995). The shoulders and arms, following the lead of the hips, accelerate to a maximum rotational velocity, ~65 ms prior to ball contact in elite players (Welch et al. 1995).

As a result of the body's coordination, the bat also moves around the vertical axis of the trunk, increasing the bat's angular and linear velocity. The two main components of linear movement are anterior (away from the body) and downward in direction. The linear motion of the bat then becomes dominant by an increase in positive direction towards the ball. It is this increase in bat speed that can lead to other benefits such as increased decision time and distance travelled by the ball (Cluck 1993).

Nearing the point of impact, the hitter utilizes the last component of angular speed and kinetic link as the speed of the bat lag or uncocking reaches its maximum value, ~20 ms prior to ball contact (Welch et al. 1995). The bat is then driven to its maximum linear velocity in unison with the right arm maximum extension velocity. Breen (1967) suggests elite hitters tend to straighten their leading forearm immediately at the beginning of the swing, however more recent research by Welch et al. (1995) suggested right arm maximum extension occurred ~15 ms prior to ball contact, indicating that it is a key performance characteristic of elite hitters to extend the arms throughout the entire swing (Cluck 1993), although more research is needed to determine the exact timing of each arm's maximum extension.

2.3.1.5 Contact

At ball contact, the body uses both coordination and position to generate bat speed and direction. The linear speed of the bat decelerates slightly, but the most significant component of that speed is directed in the positive direction toward the ball. The left leg acts as a block, applying force to the ground. An elite hitter, as suggested by Breen (1967), will keep the upper body position, after contact, in the same direction as the flight of the ball, thus putting weight on the front foot. The right leg now acts in a support capacity, flexed at the knee and applying force to the ground. The trunk moves into extension and slight right lateral flexion (Welch et al. 1995), in an effort to assist in bat position and becomes an extension of the front leg's block.

2.3.1.6 Summary

Surprisingly, given the popularity of the game, relatively few studies have undertaken detailed biomechanical analysis of baseball hitting. In particular, even fewer studies have been performed in the last 15 years. However, to specifically examine differences between good and poor hitters and between bats of varying mass it is essential to understand the biomechanics of the swing. Thus, a limited description of the swing has been provided in the current review, with the aim of highlighting key kinematic variables.

The baseball swing is initiated by a weight shift toward the back leg (Welch et al. 1995). Alternatively, Cluck (1993) suggested that the swing starts with the hitter's preparation before the pitch is delivered. Both authors described the swing up until ball contact and thus the end of the swing was defined as bat/ball contact. These authors did not consider any mechanics after bat/ball contact as the hitter can no longer influence the flight path of the ball. However, a study by Garhammer (1983) gave an analysis of the swing from the initiation to the follow through of the swing. Describing the follow through as an absorption of energy by large musculature and that a properly controlled swing would create a body position that is favourable for the legs to initiate a run to first base (Garhammer 1983).

Breen (1967) reported that successful hitters (elite hitters) show diverse, yet successful swing characteristics. Cluck (1993) suggested that it is important for hitters to keep the head still (i.e. not lifting during the swing) and that their timing is accurate (so that consistent bat/ball contact is made) throughout the entire swing. It is also imperative that the hitter's centre of gravity follows a fairly level plane throughout the swing and that maximum arm extension occurs early in the swing to allow for greater bat swing velocity (Breen 1967). Bat swing velocity is regarded as an important variable and is often a focus of coaches when

designing and implementing training programs. With these variables in mind, a coach can better observe and correct/improve a hitter's swing mechanics. Often good hitters will possess some of these variables, but it is suggested that only the great hitters can achieve all of these parameters consistently (Breen 1967). Sub-elite players are often capable of these traits as well, but maybe less able to adapt when the opposing pitcher improves their performance. Minimal research has been undertaken examining sub-elite baseball players, and thus little is known about the specific variables that constitute relatively good or relatively poor performance, and it is unclear whether the evident differences in performance are a result of psychological pressure, biomechanical fault, or other physical issues.

A player's ability appears to have a significant effect on their swing kinematics. Additionally the bat they use in training, warm-up and games will also affect swing pattern due to varying mass and length. For this reason it is equally important to examine the physical properties of the baseball bat alongside swing kinematics.

2.4 Characteristics of the Baseball Bat

There are two key components to the baseball swing; the physical and the mechanical. The physical (intrinsic) component is comprised of the kinematics and kinetics of the hitter and the mechanical (extrinsic) component pertains to the bat. Therefore, prior to a review on bat swing velocity this section gives a brief history of the baseball bat followed by an analysis of the primary physical characteristics of the bat that have been (or maybe) modified.

Many factors contribute to resultant ball velocity following bat/ball contact, including bat mass, mass distribution (moment of inertia), bat swing velocity, bat elastic performance, the

ball's coefficient of restitution, location of the ball impact on the bat, and pitch velocity (Fleisig et al. 2002; Greenwald, Penna & Crisco 2001; Hendee, Greenwald & Crisco 1998; Nathan 2000; Smith 2001). It is hypothesized that batted ball speed is dominated by two primary sources; bat swing velocity and bat characteristics (Greenwald, Penna & Crisco 2001). Specifically, swing speed is a function of both extrinsic factors (the baseball bat) and intrinsic factors (player strength, effort, and biomechanics). Ball speed at the point of bat/ball contact is determined by the swing speed, the centre of rotation of the bat, the bat/ball impact location (i.e. where the ball hits the bat) and the bat's elastic performance, which is a function of the materials and design of the bat itself (Greenwald, Penna & Crisco 2001). It is clear that the relationship between bats and batted ball speed is multifaceted, thus, there are a variety of methods that may be employed to improve performance of this skill.

HISTORY

Much has changed in batting since the origin of baseball. Most notably, players from pre-1960 tended to use heavier bats than today's players. Babe Ruth reportedly began his hitting career using a 1.5 kg hickory bat, and is known to have used a 1.1 kg bat in 1927 when he hit 60 home runs (a record for the MLB at the time). Ty Cobb and Joe Di Maggio both played with 1.2 kg bats and Rogers Hornsby used a 1.4 kg bat. Bahill and Karnavas (1991) suggest George Sisler, in the 1920's, made his bat heavier by hammering nails into the barrel of his bat and in the 1950's, Cincinnati Reds' Ted Kluszeski also hammered nails into his bat to make it heavier. More recent great hitters including Ted Williams, Rod Carew and Stan Musial used much lighter bats; 0.87-0.93 kg. Roger Maris used a 0.93 kg bat to hit 61 home runs in 1961. Interestingly, many players have tried to make their bats lighter by drilling a

hole in the barrel and filling it with cork. However, science has later proved this to be an ineffective method of improving bat performance (Nathan, Russell & Smith 2004).

Anecdotal reports suggest that Roger Maris participated in a 1962 experiment in which he batted for distance with 5 different new bats whose weights varied from 0.93-1.33 kg. He hit 5 long fly balls with each bat and the distances were measured and correlated to bat weight. The heavier bats, on average, resulted in further distance. There has been an absence of literature examining this relationship in a baseball-specific context, however, this observation was supported by the results of Fleisig et al.(2002), who showed that when swing and pitch speed remain constant, a heavier bat will produce a further hit due to increased batted ball velocity. However, Maris' preferred bat (which he used to break Babe Ruth's home run record) was the lightest of the set, even though it produced the shortest distance fly balls. Presumably, a lighter bat allows for greater bat speed and contributes to the batted ball's momentum through increased velocity and also allows for better bat/ball contact in a game situation, as the hitter has more time to see the pitch.

In 1998, Mark McGwire used a 0.99 kg bat to hit 70 home runs and Barry Bonds used a 0.9 kg bat to hit 73 home runs in 2001 (each were a MLB record). Most of today's major league players typically use 0.87-0.99 kg bats, highlighting that one major difference in today's game to that of the early 20th century is the weight of the bat being used (Ashley 1990). This component, along with other pertinent factors that contribute to hitting in baseball will be discussed below.

2.4.1 Mass and Length

The two most notable characteristics of a bat when it is first picked up by a baseballer are the bat's mass and length. Currently, the average baseball bat mass is 0.85 kg and the average length is 0.83 m (as used in games by sub-elite baseballers) (DeRenne et al. 1995). For an object such as a cylinder the rotational inertia is calculated as follows (Williams et al. 1972):

$$I = (1/4)MR^2 + (1/12)ML^2 \quad (1)$$

where

M = the mass of the bat (kg);

L = the length of the bat (m);

R = the radius (m); and

I = rotational inertia.

If either the length or the mass of the bat increases, the rotational moment of inertia increases, making the bat more difficult to swing. However, since applied force is a product of mass and acceleration, it is possible to increase the force by elevating the mass and maintaining the same acceleration. Theoretically, if it is possible to maintain bat swing technique, a heavier bat should be used, as resultant force will be greater.

2.4.2 Moment of Inertia

The length of the bat will affect the torque of the system, as it is a product of the radius of an object and the force produced. Moment of inertia (MOI) is also affected by the length of the

bat. The bat's MOI is a representation of where the mass is distributed throughout the bat. Consequently radius of gyration is affected by MOI, and furthermore the centre of percussion (COP) of the baseball bat is affected by the radius of gyration. Thus, the length of the bat can affect the sweet spot of a baseball bat, and it is generally accepted that the longer the bat, the larger the sweet spot. This is shown using the following formula (Weyrich et al. 1989, p. 200):

Moment of inertia:

$$I_o = \frac{T^2 \cdot w \cdot r}{4\pi^2} \quad (2)$$

where

T = period of time of one complete swing (s);

w = bat weight (N);

r = distance from the centre of gravity to the pivot point (m); and

I_o = moment of inertia about point o (10cm from bat knob).

Radius of Gyration:

$$k = \sqrt{\frac{I_o}{m}} \quad (3)$$

where

m = mass of the bat (kg); and

k = radius of gyration

Centre of Percussion:

$$q = \frac{k^2}{r} \quad (4)$$

where

q = centre of percussion

Fleisig et al. (2002) reported that bat linear velocity varied considerably among a selection of bats, and these variations in velocity were significantly related to bat MOI, as opposed to bat mass. Further, an approximately linear relationship between bat MOI and bat linear velocity was also found (Fleisig et al. 2002). Momentum is a product of mass and velocity, and during impact momentum is transferred from the bat to the ball. Increasing bat velocity increases the bat's momentum, momentum transfer, and resultant ball velocity. However, reducing a bat's mass and MOI decrease the bat's effective mass, resulting in decreased resultant ball velocity (Fleisig et al. 2002). Therefore, it is optimal to decrease a bat's MOI, without reducing its mass. In practice this is difficult to achieve, due to the baseball bat's physical properties along with the rules governing length and mass.

The impact location of the ball on the bat has a significant effect on resultant ball velocity. Specifically, Weyrich et al. (1989) reported that post-impact ball velocities were significantly greater when impact occurred at the COP ($10.66 \text{ m}\cdot\text{s}^{-1} \pm 0.22$) rather than at two off centre locations; centre of gravity ($8.32 \text{ m}\cdot\text{s}^{-1} \pm 0.22$) and one toward the end of the bat ($5.69 \text{ m}\cdot\text{s}^{-1} \pm 0.27$). Further, it has been stated that the COP is the point of impact that will result in a maximum transfer of energy from the bat to the ball, thus maximizing resultant ball velocity (Noble & Eck 1986). Bryant et al. (1977) showed that off-centre impacts produced up to 2000% greater reaction impulses at the handle when compared to COP impacts, suggesting that off-centre impacts reduce the energy transferred to the ball.

However, each of the researchers (Bryant et al. 1977; Noble & Eck 1986; Weyrich et al. 1989) noted that since not every impact point on the bat had been tested, it was not possible to conclude that COP was the optimum point of contact.

2.4.3 Coefficient of Restitution

Coefficient of restitution (COR) has a significant effect on post-impact ball velocities as “the coefficient of restitution is the ratio of the final relative velocity to the initial relative velocity of the colliding objects” (Kagan 1990, p. 151). The COR is represented by the following formula (Bahill & Karnavas 1991, p. 25):

$$e_o = -\frac{v' - V'}{v - V} \quad (5)$$

where

e_o = coefficient of restitution;

v = initial velocity of ball ($\text{m}\cdot\text{s}^{-1}$);

v' = final velocity of ball ($\text{m}\cdot\text{s}^{-1}$);

V = initial velocity of bat ($\text{m}\cdot\text{s}^{-1}$);

V' = final velocity of bat ($\text{m}\cdot\text{s}^{-1}$).

Ball COR is most commonly used to predict ball performance and is used as an indicator of ball ‘liveliness’ (the ability of the ball to store and translate energy), which is dependent upon the material composition and construction of the ball (Hendee, Greenwald & Crisco 1998). The COR is also a function of ball velocity as along with the mechanical properties and shape of the target (the bat).

2.4.4 Aluminium vs. Wood

When considering resultant ball velocity after ball-bat impact, aluminium bats are generally more effective than wooden baseball bats. An excerpt taken from Adair (1995, p. 6) explains this process:

“When the ball hits the wooden bat, the bat compresses about 2% as much as the ball – and hence stores about 2% of the collision energy. The ball, with a coefficient of restitution at high velocities of about 0.45, returns about 20% of its 98% of the stored energy, while the bat, which is about as elastic as the ball, returns about the same proportion. By contrast, the hollow aluminium bat is distorted about 10% as much as the ball by the collision and so stores about 10% of the collision energy. And it returns that energy efficiently – probably at a level of about 80%. Adding the ball and bat contributions, about 26% of the collision energy is returned, and the ball leaves the aluminium bat with a higher velocity.”

Greenwald et al. (2001) demonstrated that metal bats yield better results (higher resultant ball velocities) than wooden bats. This was attributed to decreased MOI and bat elasticity (combination of bat materials and bat design). Nicholls et al. (2003) agreed with this proposal, showing that an aluminium bat (MOI - $0.269 \text{ kg}\cdot\text{m}^2$) produced a higher batted ball velocity ($44.3 \text{ m}\cdot\text{s}^{-1} \pm 2.5$) than a wooden bat (MOI - $0.329 \text{ kg}\cdot\text{m}^2$) which returned a velocity of $41.7 \text{ m}\cdot\text{s}^{-1} \pm 1.9$. Bryant et al. (1977) performed laboratory studies and found that aluminium bats have a larger COP, as response impulses remained lower for longer as the ball move away from the COP. They proposed that this was probably due to the fact that wooden bats are comprised of a solid, yet “heterogeneous material while aluminium bats are hollow and more homogeneous” (Bryant et al. 1977, p. 509). Due to the nature of the material, it is therefore easier to modify aluminium bats, more specifically change its

moment of inertia. The current study used wooden bats, as this is the type of bat used in the majority of sub-elite Australian baseball leagues.

2.5 Bat Swing Velocity

Possible outcomes of improving bat swing velocity include (but are not limited to):

- increased decision time;
- greater batted ball speed, and;
- increased distance travelled by the ball.

Increasing the time to decide to hit the ball is important in baseball as it allows the batter more time to see the pitch before they commit to a swing (Sergo & Boatwright 1993), which can lead to better ball contact and consequently better game performance. Increasing batted ball speed gives the ball a greater chance of travelling further, but importantly, also makes it more difficult for the fielder to field the ball, as they have less time to react to the hit ball (Nicholls et al. 2003). These theoretical effects are presented in Figure 2.3. If other variables (such as pitch speed, wind speed, and point of contact) remain constant, and bat swing velocity is improved, then the ball will travel further (Sawicki, Hubbard & Stronge 2003). This effect may lead to a ball clearing the infield, passing over an outfielder, or more significantly it may result in hitting a home run.

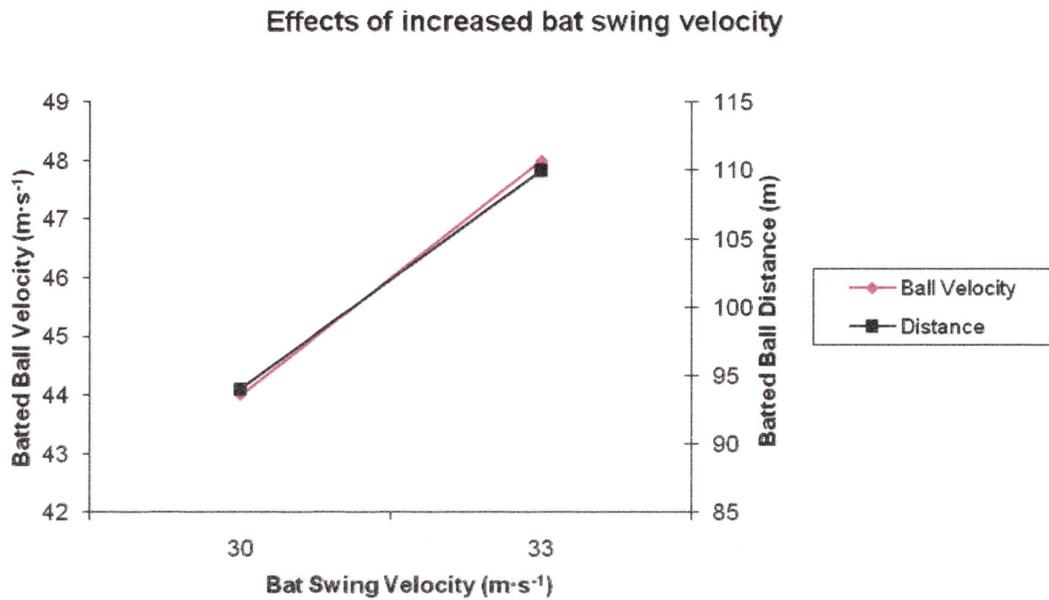


Figure 2.3 – Theoretical effects of increased bat swing velocity. Assuming a pitched ball speed of $40\text{m}\cdot\text{s}^{-1}$, a take off angle of 35 degrees, and neglecting wind and air resistance.

Recent research has shown that the integration of weight training and sport specific resistance training in a comprehensive periodised program will lead to optimal athletic performance (Szymanski 1998). The baseball swing is fundamental to the game of baseball and an increase in bat swing velocity may be beneficial to the batter. Thus, any training and/or warm-up techniques (such as manipulating bat mass) that improve bat swing velocity would prove to be worthwhile and should be incorporated into a player's regime.

2.5.1 Acute Methods for Improving Bat Swing Velocity

During a baseball game it is a common practice to warm-up by swinging a modified bat (most commonly a heavier implement is used) before stepping into the batter's box (Southard & Groomer 2003). Such a rationale is based on the hypothesis that the batter will gain an acute augmented neuromuscular response enabling them to increase bat swing

velocity during performance. DeRenne (1982) examined the effects of warm-up on bat swing velocity with weighted implements (donut ring, power swing, and a weighted bat), variable speed training implements (underweight bats), and a standard game bat. A total of 23 baseball players were used in the study including current and former college players, and professionals playing in a semi-professional league. On separate days, the players used a different warm-up protocol prior to swinging a standard baseball bat (their game bat). A photosensing computer was used to measure bat swing velocity. It was found that very heavy and very light warm-up implements had adverse effects on bat swing velocity, whereas the weighted bat and slightly lighter bat showed enhancement in bat velocity (DeRenne 1982), although no specific data was given.

Based on a review of his previous works DeRenne (1991) recommended that the quickest game bat velocity was achieved by using warm-up implements having identical or very close weights to the standard 0.85kg game bat. It was concluded that implements used prior to performance should not exceed $\pm 10\%$ of the standard mass, specifically it was reported that the 0.82kg underweighted bat was the best choice for improving bat swing velocity in the resultant match situation (DeRenne 1991).

A further study by DeRenne et al. (1992) included warming up with 13 different weighted batting implements, with the aim of investigating the effects of each on bat swing velocity. For this study, 60 high school baseball players were used and tested on 13 separate days (a different implement each day). The top three bats (by mass) to yield the highest bat velocity post warm-up were the 0.82kg, 0.96kg and 0.85kg bats. Specifically, bat swing velocities after warm-up were $27.1 \text{ m}\cdot\text{s}^{-1}$, $26.6 \text{ m}\cdot\text{s}^{-1}$ and $26.5 \text{ m}\cdot\text{s}^{-1}$, respectively (Table 2.2). The most significant finding from this study was that the donut ring, which is the most commonly used warm-up implement in both sub-elite and elite baseball, consistently resulted in the slowest bat velocities ($24.5 \text{ m}\cdot\text{s}^{-1}$) post warm-up (DeRenne et al. 1992).

Table 2.2: Bat Velocity after warm-up with bats of varying mass (adapted from De Renne et al. (1992, p. 216)).

Bat Mass (ounces; kilograms)	Bat Swing Velocity Post Warm-Up ($m \cdot s^{-1}$)	S.D.
29; 0.822	27.1	0.85
34; 0.963	26.6	0.85
30; 0.850	26.5	0.71
27; 0.765	26.5	0.89
42; 1.190	25.6	0.71
25; 0.708	25.5	0.94
45; 1.275	25.4	0.71
48; 1.360	25.0	0.67
23; 0.652	24.6	0.85
51; 1.445	24.6	0.76
Donut – 58; 1.644	24.5	0.71

More recently, baseball bat swing velocity and swing pattern were measured during a study using experienced baseballers who were required to swing a bat 5 times under 3 conditions: standard bat; standard bat with donut ring; and, a hollow plastic bat (Southard & Groomer 2003). Following this, a standard game bat was swung 5 times and bat swing velocity and swing pattern were recorded. The results demonstrated that swinging the weighted bat (donut ring) prior to performance produced the slowest bat swing velocity (20% less than using a standard bat). Further analysis of the swing pattern suggested that increasing the moment of inertia of the warm-up bat saw a reduction of the lag between the leading wrist and the leading elbow joint and an associated lack of velocity transfer from the leading elbow joint to the leading wrist joint (Southard & Groomer 2003). Such a pattern change reflects a poorly organised open kinetic chain and was accompanied by a reduction in bat velocity. These results support those suggested by DeRenne et al. (1992), who showed adverse effects on velocity when using bats $\pm 10\%$ of regulation mass for warming up.

The above mentioned studies indicate that batters are better served warming up with a bat with a similar mass to what they intend to use in the game. Moreover, Southard & Groomer's (2003) research is the only study to examine swing kinematics in this context and

report that using a bat with a larger moment of inertia (primarily increased bat mass) not only slows down the swing, but may also change the batter's swinging pattern. Although this is not advisable immediately prior to performance, there has been a notable interest into the longitudinal effects of training with bats of varying mass, due to implications associated with an improvement in bat swing characteristics.

2.5.2 Training Methods for Improving Bat Swing Velocity

The majority of research (DeRenne 1982, 1987; DeRenne et al. 1995; DeRenne & Okasaki 1983; Sergio & Boatwright 1993) has indicated that training to increase bat swing velocity should be performed with a baseball bat, performing replica swings to that used in a game so that training occurs at a similar velocity to competition. This notion of velocity specificity of training is widely documented across a range of different activities (Almasbakk & Hoff 1996; Behm & Sale 1993a, 1993b; Cronin, McNair & Marshall 2002; Kanehisa & Miyashita 1983; Kaneko, Fuchimoto & Toji 1983; Kawamori & Newton 2006; Pereira & Gomes 2003; Wilson et al. 1993) and dictates that performance enhancement will occur at or near the velocity at which training occurred.

Strength training is believed to increase strength to the greatest degree at the specific velocity of movement at which training is performed. Therefore, performance improvements gradually decrease at velocities farther away from the training velocity (Almasbakk & Hoff 1996; Behm & Sale 1993a, 1993b; Cronin, McNair & Marshall 2002; Kawamori & Newton 2006). It would also be of benefit if these movements were trained with a high resistance (without sacrificing velocity) to encourage muscular growth (Almasbakk & Hoff 1996). Kawamori and Newton (2006) suggest that movements should maximise the acceleration

phase and minimise the deceleration phase. Therefore, when considering a baseball swing specifically, emphasis should be placed on swing initiation through to ball contact.

The improvements demonstrated with the use of a velocity specificity approach to resistance training are due primarily to neuromuscular adaptations (Behm & Sale 1993a; Kaneko, Fuchimoto & Toji 1983; Pereira & Gomes 2003). Specific effects of training, relating to different load conditions, could suggest that different mechanisms such as alteration in muscle property and motor neuron activation may be responsible for a specific shift in force-velocity relation and resultant power output (Kaneko, Fuchimoto & Toji 1983). Accordingly an improvement in bat swing velocity due to velocity specific training could be a result of a change in muscle property rather than an increase in hypertrophy (muscle size).

Implement weight training involves exercising with modified competitive elements (baseball bats) while duplicating the acceleration-performance through a full range of motion, in a safe manner (DeRenne 1987). A baseball player should exercise according to specific training regimes and the mass of implements should be close to that of a standard one used in competition. The following research (review on longitudinal training studies) shows that if implements are precisely heavier or lighter, with the correct training loads, the player will be replicating the performance range of motion and producing force-power output for an increase in bat swing velocity (DeRenne 1987).

A study by Sergo and Boatwright (1993) investigated whether bat swing velocity could be improved by training with a combination of weighted (1.75kg) and light (fungo) bats at the same time, as opposed to training with a weighted or regulation bat alone. Twenty-four college baseballers were pre-tested for bat swing velocity, using a 0.87kg bat, swinging through a light timing device 10 times. During testing the average of the final 5 trials was taken as the measurement, and the light timing device was designed so that the beams were

45.72cm apart (reflective of the contact zone in hitting). The researchers defined where the hitter would make contact with the ball previous to actual testing, therefore making the measurement subjective. Thus, the measurement was not precise to bat swing velocity at ball contact.

The subjects were randomly assigned into three groups. A control group (group 1) used a National Collegiate Athletic Association (NCAA) regulation game bat of their choice (most popular game bats have a mass between 0.82-0.85kg). The weighted bat group (group 2) used a 1.75kg bat and the combination training group (group 3) alternated between a 1.75kg bat and a fungo bat. The fungo bat mass was not specified in this study, but is traditionally between 0.48 and 0.62kg. All three groups completed a training program that consisted of 100 dry swings per session, three sessions per week, for six weeks. The combination training group performed 50 swings of each bat within a single session. The training sessions comprised of 20 sets of 5 swings with no more than 20 seconds rest between each set. Swings were monitored and subjective feedback was given based on Race (1961) and Breen (1967) to enforce correct swing pattern. Aluminium bats were used for this study.

All three groups showed significant improvements in bat swing velocity (Table 2.3), however there were no between group differences. It must also be noted that the regulation game bat in this study may be considered underweight training, as the players choice of bat may have fallen under the testing bat mass of 0.87kg.

Table 2.3: Group mean bat swing velocities and percent change (Sergo & Boatwright, 1993).

Training Group	Pre-Test (m·s ⁻¹) (SD)	Post-Test (m·s ⁻¹) (SD)	Percent Change (Significance)
1	41.71 (5.50)	45.40 (2.41)	8.8% (p ≤ 0.05)
2	40.36 (3.74)	43.58 (3.47)	8.0% (p ≤ 0.05)
3	41.52 (3.14)	44.92 (4.20)	8.2% (p ≤ 0.05)

It was concluded that swinging a bat of any mass 100 times a day, three days a week for six weeks can significantly improve bat swing velocity (Sergo & Boatwright 1993). The length of this study was chosen to mimic the length of a college pre-season, as this would be the ideal time to implement this type of training. The training was incorporated into the player's regular baseball training sessions, which implies that results cannot be specifically derived from weighted implement training alone.

A more comprehensive study by DeRenne et al. (1995) concluded that bat swing velocity improvements can be attributed to a training protocol that involves swinging and hitting with bats of varying mass. The study used 60 division one college baseball players, with an average age of 19.5 years (DeRenne et al. 1995). Subjects were pre- and post-tested by swinging a standard bat (0.85 kg) through two light beams 10.16cm apart. These were attached to a photosensing computerized timer.

Subjects were randomly assigned to one of three groups. The control group (CG) used a standard game bat, with a mass of 0.85kg. Both the batting practice group (BP) and the dry swing group (DS) used a combination of underweighted bats ranging from 0.76-0.82kg and overweighted bats ranging from 0.87-0.96kg. Both the CG and DS groups were instructed to dry-swing (i.e. no ball contact was made) a bat 150 times a day. The BP group hit pitched baseballs 150 times a day. No other batting practice or weight training took place within the 12 week period. Thus, the prescribed training was reflective of regular batting practice load.

Every week, each group completed 4 sessions of their prescribed training. The BP and DS groups alternated heavy, then light, then standard weighted bats (10 swings per bat per set, for 5 sets, with no more than a 15sec rest between each bat and no more than 30sec rest between sets for a total of 150 swings (DeRenne et al. 1995). The mass of the bats for BP and DS fluctuated up and down by 0.02kg every 3 weeks, except during the final 3 weeks whereby the underweight bat remained at 0.76kg. During the training schedule (Table 2.4), training swings for all three groups were monitored and corrections made, as identified by Breen (1967) and Race (1961).

Table 2.4: Training Schedule (DeRenne et al., 1995, pp. 248).

Weeks	Total Swings	Sequence of Swings	Weight of bats (oz)
Batting Practice Group			
1-3	150	50/50/50 (H/L/S)	31, 29, 30
4-6	150	50/50/50 (H/L/S)	32, 28, 30
7-9	150	50/50/50 (H/L/S)	33, 27, 30
10-12	150	50/50/50 (H/L/S)	34, 27, 30
Dry Swing Group			
1-3	150	50/50/50 (H/L/S)	31, 29, 30
4-6	150	50/50/50 (H/L/S)	32, 28, 30
7-9	150	50/50/50 (H/L/S)	33, 27, 30
10-12	150	50/50/50 (H/L/S)	34, 27, 30
Control Group			
1-3	150	50/50/50 (S/S/S)	30
4-6	150	50/50/50 (S/S/S)	30
7-9	150	50/50/50 (S/S/S)	30
10-12	150	50/50/50 (S/S/S)	30

Note: S = standard bat, H = heavy bat, L = light bat

Groups were retested after 12 weeks of training and each showed significant improvements ($p < 0.05$) in bat swing velocity (see Table 2.5). It is important to note that the BP and DS groups showed significant improvement compared to the CG. Additionally the BP group showed significantly more improvement ($p < 0.001$) than the DS group (DeRenne et al. 1995).

Table 2.5: Group mean bat swing velocities and percent change (DeRenne et al., 1995).

Training Group	Pre-Test ($\text{m}\cdot\text{s}^{-1}$) (SD)	Post-Test ($\text{m}\cdot\text{s}^{-1}$) (SD)	Percent Change (Significance)
BP	34.6 (2.1)	38.0 (2.3)	9.8% ($p = 0.0001$)
DS	35.8 (3.4)	37.8 (2.9)	5.6% ($p = 0.0001$)
CG	35.9 (2.8)	36.4 (2.6)	1.4% ($p = 0.03$)

It was suggested that using a combination of weighted bats could serve as an adjunct training method to significantly improve bat swing velocity in collegiate baseballers (DeRenne et al. 1995). The findings also suggest that either the batting practice or dry swing protocol would significantly improve bat swing velocity ($p < 0.05$) (DeRenne et al. 1995). According to the results, if the implements are no more than 12% heavier or lighter than a standard baseball bat and correct resistance load ratios are used, then bat swing velocities will increase significantly. DeRenne et al. (1995) also used a light timing device, however mean bat swing velocity differed by over $7 \text{ m}\cdot\text{s}^{-1}$ between studies (using subjects of similar nature), thus calling into question the validity of such methodology. Overall, it appears that the use of such methodology does not accurately account for maximum bat swing velocity.

2.6 Summary

Elite hitters show a variety of swing characteristics (Breen 1967), however each specific trait appears to contribute to increased bat swing velocity. The acute effects (warm-up) of using weighted implements to improve bat swing velocity are detrimental to performance and bat swing technique (Southard & Groomer 2003), unless they are close to the mass of the bat used in the game (DeRenne 1982, 1991; DeRenne et al. 1992). Weighted implement training involves exercising with modified baseball bats while duplicating the velocity specific swing traits used in

game performance, in an attempt to increase bat swing velocity. Research has indicated that weighted implement training can be effective in enhancing bat swing velocity by approximately 10% (DeRenne et al. 1995; Sergio & Boatwright 1993). The existing literature suggests the bat mass to use when training has been shown to be no more than 12% heavier or lighter than a standard baseball bat (DeRenne et al. 1995). However, it is unknown whether bat swing velocity differentiates players of varying ability or whether training induced changes in bat swing velocity transfer through to game performance.

CHAPTER 3

METHODS

3.1 Overview

The primary aim of the study was to describe the biomechanics of the baseball swing using bats of different mass. In addition, differences in the biomechanics of the swing between relatively good and relatively poor hitters were investigated. A cross sectional study was undertaken with sub-elite baseballers, investigating the effects of bat mass on batting swing variables including bat speed, joint angles, body segment velocities, and stride length. Twenty sub-elite baseballers were instructed to hit a ball 30 times off a hitting tee, replicating a 'line drive hit', using three different bat masses. To analyse bat swing kinematics, a three dimensional infrared camera system was positioned to capture each subject's swing.

3.2 Participants

Twenty healthy male, sub-elite baseballers (22.3 ± 5.3 yrs, 1.70 ± 0.07 m, 83.5 ± 10.9 kg) were recruited from the New South Wales Major League (NSWML) via letters, flyers and internet postings. The NSWML is the second tier baseball league in Australia, which provides players to the Australian Baseball League (ABL) and various other professional leagues internationally. Each gave written informed consent (Appendix 1) to participate in the research, which was approved by the University of Technology, Sydney Human Research Committee (HREC#2008-181A). All participants completed a medical and physical activity questionnaire (modified Healthscreen, Appendix 2), informing the researchers that they were fit for

testing and that there was no difference between the groups in activity level. None of the subjects that took part in the current study had sustained a musculoskeletal injury prior to data collection. All tests were conducted on site in the gymnasium at the Kuring-Gai campus of the University of Technology, Sydney.

The participants were informed that the testing would result in a baseball bat swing velocity profile, with the tests providing a comprehensive overview of their batting biomechanics. They were also informed that they would receive a written report (and verbal report if requested) with comparative values to their peers. In accordance with ethical guidelines, all results remained anonymous except to the individual undertaking each test. The testing procedures were explained in detail, with adequate time available for feedback and/or questions.

Prior to testing, all participants were rated based on two criteria. The first was the qualitative ratings of three level 2 coaches (issued by the Australian Baseball Federation, approved by the Australian Sporting Commission) who observed their technique in person. The second criteria considered the seasonal batting averages of each player. This data was used in the statistical analysis to distinguish relatively good and relatively poor hitters within the sample.

Sample size was determined by priori using measures of effect size based on a review of the literature. It was anticipated that the effect size differences for the in BSV between the two groups would be quite large ($d = 0.7-0.9$). Therefore, with an

effect size estimate of 0.8 and an alpha level of 0.05, the minimum sample size for each group was 9 (Kraemer & Thiemann 1987).

3.3 Testing Procedures

Participants were required to attend testing on one day for a period of approximately 60 minutes. The testing protocol was explained to each participant and they were then encouraged to ask questions if they did not understand any of the procedures. Participants had their height recorded on a stadiometer (Holtain, United Kingdom) and their body mass recorded using a set of electronic, calibrated scales (A & D Mercury, Australia).

Prior to data collection, a system of 16 reflective markers was placed on the participant, bat and ball. A spatial model was created for 3D kinematic analysis, using similar locations to previous research (Escamilla et al. 2009; Southard & Groomer 2003; Welch et al. 1995). The markers were firmly attached to each subject using rigid sports strapping tape (Beiersdorf, Australia). To assist in marker application, subjects were instructed to wear tight fitting clothing. Markers for the bat were attached using double sided adhesive tape (3M, St. Paul, Minnesota). The ball was partially covered in reflective tape (Reflexite, Darra, Australia) and represented one marker. As depicted in Figure 3.1, marker placement included the bat end, bat knob, ball, proximal midline of the subject's forehead, and both sides of the body for the coracoid process, lateral aspect of the head of the radius, distal

radioulnar joint, iliac crest, proximal superior patella and posterior aspect of the calcaneus. All participants were right handed hitters.

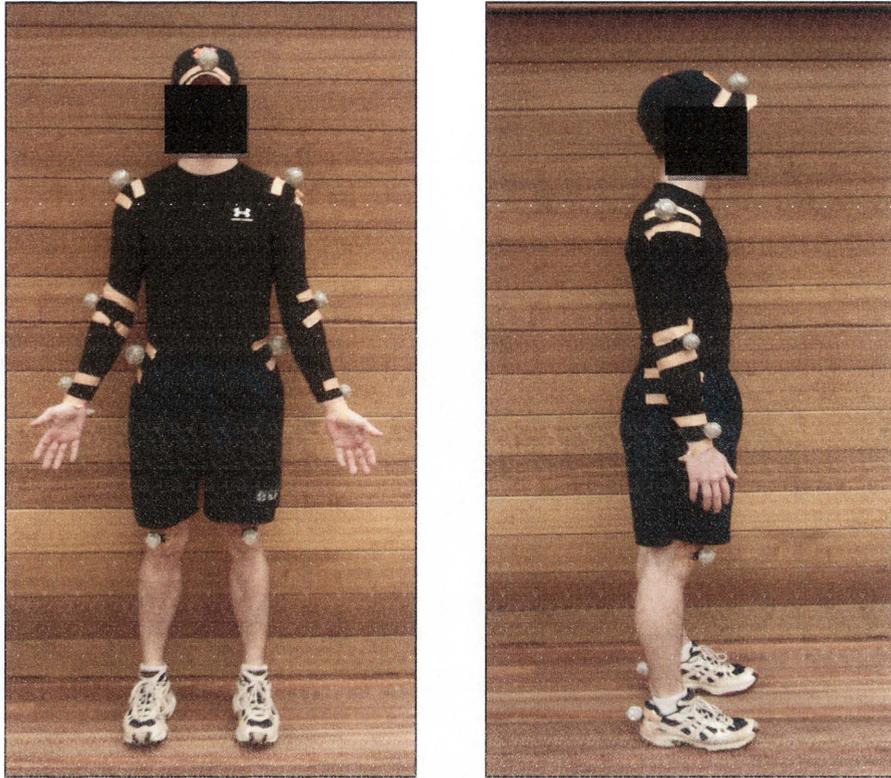


Figure 3.1 – Marker Placement on the Subject

Following the application of markers, each participant completed a standardised warm up routine. The participant performed a 5 min cycle on a stationary bike (Monark 818 E, Monark, Sweden) at 50 Watts and was then permitted to perform individualised static stretching of the upper and lower body. The participant was then instructed to perform ten practice swings with no ball contact. To complete the warm-up, the participant performed five contact swings (with a regulation game bat)

that replicated the testing procedure. During the contact swings, the markers were checked by the researcher to ensure they were securely attached.

A batting tee (Ez Tee, PIK Products, Norwalk, Connecticut) was placed in a hitting area and adjusted to the participant's preferred position. The average tee height for all subjects was $40 \pm 2\%$ of their stature. Participants were then instructed to hit 10 baseballs (A1010S, Wilson, Chicago, Illinois) off the tee and into a net with the intent of hitting a 'line drive up the middle'. A 45 second rest period was allowed between each swing. Criteria for determining a successful swing included verbal feedback from the participant (a score between 1-5 was given), clean solid contact and flight path of the ball (measured from the three dimensional data captured). Upon completion of the 10 impacts, the process was then repeated for each of the other two bats in random order. All bats were visually identical and subjects were not informed of the bat's physical properties (Figure 3.2). The order of bats used was randomized for each participant.

Bats used in this study were custom made from White Ash (Phoenix Bat Company, Columbus, Ohio) and had the following dimensions (Length/Mass):

- Bat₁ - 0.838m/0.795kg (33in/28.04oz)
- Bat₂ - 0.838m/0.847kg (33in/29.87oz)
- Bat₃ - 0.838m/0.943kg (33in/33.26oz)



Figure 3.2 – The baseball bats of varying mass used in the current study (Bat₁, Bat₂, Bat₃).

3.4 Data Collection

During data collection, the motion of the reflective markers in space was simultaneously captured by four infra-red cameras at a rate of 240 frames per second (Qualysis AB, Gothenburg, Sweden). Each camera was mounted on a tripod set at a height of approximately 2.6m and placed around the batting tee (Figure 3.3). These heights were determined from pilot work which maximised the field of view allowing all markers to be detected during the swing. The cameras were calibrated using a calibration frame and wand. These were positioned to include the trajectory of the bat through a normal swing as well as the batted baseball over a distance of approximately three metres (Greenwald, Penna & Crisco 2001). The hitter was

instructed to swing in response to a computer generated auditory signal, which automatically triggered a two second data collection period. The three dimensional position of each marker was collected by each of the four cameras and mathematically processed using digitizing software (Qualysis AB). The path of the bat and ball were defined using the automated algorithms and user interaction in Qualysis motion capture software. A single data file containing 3D coordinates of all markers for each swing was generated and exported from Qualysis. The Z-direction was defined as vertically upward. The X-direction was defined as a vector pointing from the tee to the net, perpendicular to the Z-direction. The Y-direction was defined as the cross product of Z and X and refers to any lateral displacement of the intended ball path. To ensure accuracy of measurement in the current study, technical error of measurement (TEM) and interclass correlation (ICC) were calculated for both angles and distances. Overall TEM for angles was less than 1% with an ICC of 1.00 and TEM for overall distances was 1.09% with an ICC of 1.00.

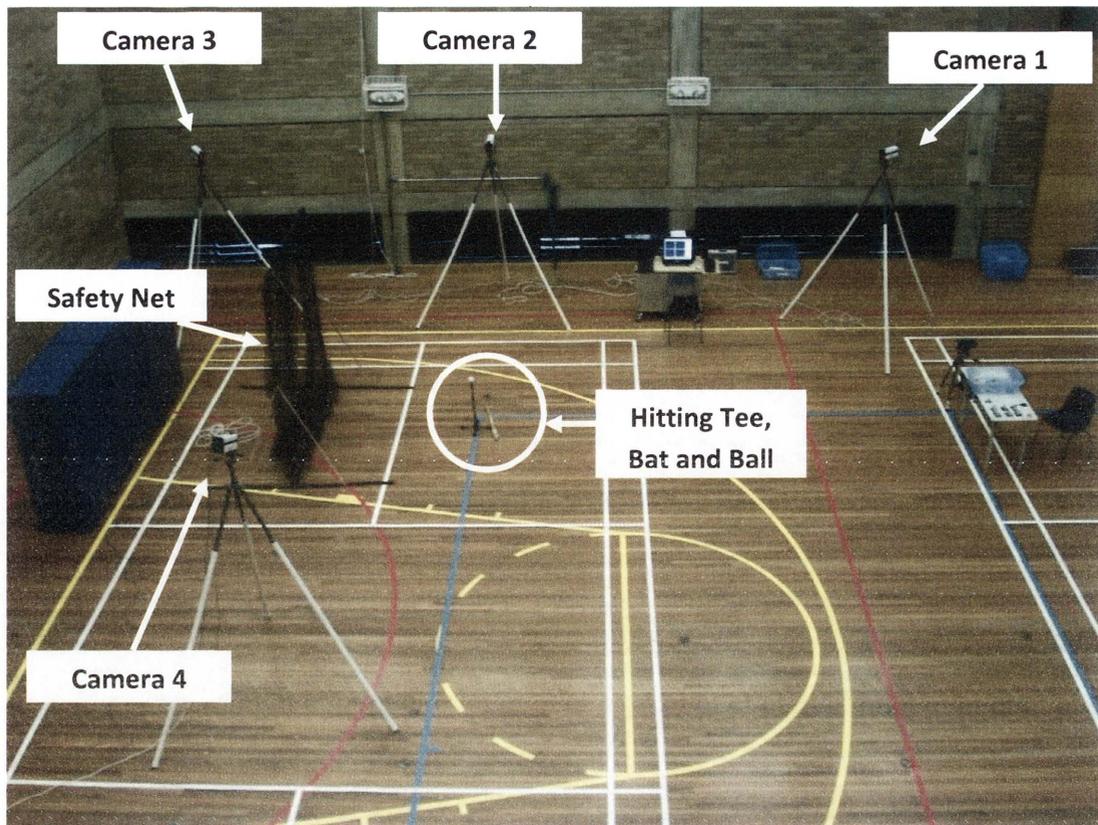


Figure 3.3 – Camera set-up surrounding batting tee and hitting net.

3.5 Data Processing

Data files were processed using QTools (Innovision Inc., Warren, Michigan) to calculate bat swing biomechanics (Table 3.1). To smooth the raw data for each digitized point, data were filtered using a fourth-order, zero phase shift, low pass Butterworth digital filter with a cut-off frequency of 13.3 Hz (Dun et al. 2007; Welch et al. 1995). Variables were processed for the subject's best five swings with each bat. These swings were determined by a feedback rating given by the subject after each swing. Where two swings were ranked evenly, the resultant ball speed after

contact was used to distinguish which swing would be processed. In this event, the swing yielding the higher ball speed was utilised.

Table 3.1: Biomechanical variables calculated for the bat swing.

Group	Measurement	Variable
Swing	Time	Swing Initiation, Bat/Ball Contact, Swing Duration
	Distance	Stride Length, Lead Foot Height off ground, Head Movement
Angle	Bat/Ball Contact	Left Elbow, Right Elbow, Left Knee, Right Knee
	Minimum	Left Elbow, Right Elbow, Left Knee, Right Knee
	Maximum	Left Elbow, Right Elbow, Left Knee, Right Knee
Angular Velocity	Bat/Ball Contact	Left Elbow, Right Elbow, Left Knee, Right Knee
	Maximum	Left Elbow, Right Elbow, Left Knee, Right Knee, Hip Segment
Linear Velocity	Bat/Ball Contact	Bat End, Ball, Left Hip, Right Hip, Left Elbow, Right Elbow, Left Wrist, Right Wrist
	Maximum	Bat End, Left Hip, Right Hip, Left Elbow, Right Elbow, Left Wrist, Right Wrist
Linear Displacement	Towards the ball	Left Hip, Right Hip

*A more detailed description of how the variables were identified can be found in Appendix 3.

Inter-trial reliability was calculated using Cronbach's Alpha for several key outcome measures (including head movement, ball velocity, various angular velocities and bat swing velocity). Reliability coefficients were moderate to high ranging from 0.81 to 0.89 which was considered acceptable for the current analysis.

3.6 Data Analysis

All data was entered into SPSS (Version 17, Chicago, Illinois) for statistical analysis. Initial analysis involved the calculation of descriptive statistics for all variables. Each set of data was tested for normality using Shapiro-Wilk's test and for homogeneity of variance using Levene's test. All data was deemed normal with homogeneity of variance. To analyze differences in the biomechanics of the swing (Table 3.1) for each baseball bat, a repeated measures ANOVA was performed with Tukey's post-hoc tests, with bat mass being the independent variable. A significance level of 0.05 was set *a priori*.

To assess whether the biomechanics of the swing differed between relatively good and relatively poor hitters, subjects were ranked according to the coach's rating and seasonal batting averages (for Bat₂ only) and divided into two groups of equal number using a median split. Although this method of discrimination was arbitrary, it created two groups of hitters of differing ability. Differences between groups in the biomechanical variables listed in Table 3.1 were assessed using a one way ANOVA.

Finally, in order to identify any relationships between bat swing velocity and other biomechanical measures, Pearsons correlation coefficients were calculated. The correlation system used involves trivial (0.0), small (0.1), moderate (0.3), large (0.5), very large (0.7), nearly perfect (0.9) and perfect (1) score, in order to signify the strength of the relationship (Hopkins et al. 2009).

Given the use of multiple comparisons, Bonferroni corrections were considered for the current study, but not used. This was due to the ongoing debate as to their usefulness in producing accurate differences (Bland & Altman 1995; Perneger 1998). The argument against the use of Bonferroni corrections suggests that the procedure is overly stringent, and whilst reducing the chance of making a type I error, the chances of producing a type II error are increased, thus increasing the possibility of incorrectly determining that no difference exists.

CHAPTER 4

RESULTS

4.1 Overview

This chapter is divided into two sections, firstly presenting differences in bat swing kinematics between relatively good and relatively poor hitters and secondly showing differences in bat swing biomechanics using bats of varying mass. Key variables that were measured included; maximum bat swing velocity (BSV_{max}), bat swing velocity at contact (BSV_{con}), resultant maximum ball velocity (BV_{max}) and left elbow maximum angular velocity ($LEAV_{max}$).

4.2 Relatively Good vs. Relatively Poor Hitters

Kinanthropometric data for each group are presented in Table 4.1. One-way ANOVA showed that there were no significant differences for age, mass and height between the two groups of varying ability.

As depicted in Table 4.2, the one-way ANOVA for bat swing kinematics demonstrated that the good group swung the bat 9% faster and batted the ball 6.9% faster than the poor group ($p < 0.05$). In addition, the good group produced 35.9% greater left elbow angular velocity ($p < 0.05$, Table 4.3). They also had a right knee angle at contact that was 5% larger than the relatively poor group (Table 4.4).

When considering bat swing velocity at contact, the results from the one-way ANOVA illustrated that the mean of the good group was 12.4% higher (non-significant) compared to the poor group (Table 4.2). The *p* value of 0.10 suggests further research is needed to confirm this difference. No significant differences were found for swing duration (Table 4.2) and head movement (Table 4.3) between the two groups.

Table 4.1: Kinanthropometric data for each group (mean \pm SD).

Kinanthropometric Variable	Total group (n= 20)	Good group (n= 10)	Poor group (n=10)	P value
Age (yrs)	21.8 \pm 5.9	21.6 \pm 2.2	22.0 \pm 8.4	0.90
Height (m)	1.83 \pm 0.08	1.82 \pm 0.09	1.84 \pm 0.07	0.54
Mass (kg)	81.1 \pm 9.2	83.33 \pm 12.7	78.87 \pm 2.9	0.39

Table 4.2: Results for all participants and comparative data for the good group and poor group for bat swing kinematics (mean \pm SD).

Kinematic Variable	Total group (n= 20)	Good group (n= 10)	Poor group (n=10)	P value
Bat				
Linear Velocity at Contact (m·s ⁻¹)	30.1 \pm 4.0	31.8 \pm 3.8	28.3 \pm 3.6 [#]	0.10
Maximum Linear Velocity (m·s ⁻¹)	35.3 \pm 3.0	36.8 \pm 3.1	33.8 \pm 2.1*	0.05
Swing Duration	0.275 \pm 0.05	0.272 \pm 0.06	0.277 \pm 0.05	0.88
Ball				
Maximum Linear Velocity (m·s ⁻¹)	36.8 \pm 2.3	38.0 \pm 2.4	35.6 \pm 1.4*	0.04

* Significant at the 0.05 level. [#] Approached significance ($p = 0.1$).

Table 4.3: Upper body bat swing kinematics (mean \pm SD).

Kinematic Variable	Total group (n= 20)	Good group (n= 10)	Poor group (n=10)	P value
Head				
Head Movement (m)	0.09 \pm 0.07	0.086 \pm 0.06	0.088 \pm 0.09	0.96
Left Elbow				
Maximum Angle (°)	144 \pm 12.1	149 \pm 10.8	140 \pm 12.4	0.18
Angle at Contact (°)	143 \pm 13.3	148 \pm 12.1	138 \pm 13.7	0.17
Maximum Angular Velocity (°·s ⁻¹)	860 \pm 267.1	991 \pm 229.7	729 \pm 248.3*	0.05
Time from Maximum Angular Velocity to Ball Contact (s)	0.015 \pm 0.028	0.010 \pm 0.022	0.021 \pm 0.033	0.68
Right Elbow				
Maximum Angle (°)	133 \pm 10.6	132 \pm 11.3	134 \pm 10.8	0.74
Angle at Contact (°)	132 \pm 12.8	131 \pm 15.2	134 \pm 11.1	0.68
Maximum Angular Velocity (°·s ⁻¹)	1896 \pm 473.7	1907 \pm 614.2	1886 \pm 329.7	0.94

* Significant at the 0.05 level.

Table 4.4: Lower body bat swing kinematics (mean \pm SD).

Kinematic Variable	Total group (n= 20)	Good group (n= 10)	Poor group (n=10)	P value
Left Knee				
Maximum Angle ($^{\circ}$)	137 \pm 8.5	136 \pm 7.0	138 \pm 10.0	0.73
Left Knee Angle at Contact ($^{\circ}$)	136 \pm 7.9	136 \pm 7.1	137 \pm 9.3	0.81
Maximum Angular Velocity ($^{\circ}\cdot s^{-1}$)	359 \pm 116	386 \pm 81	331 \pm 150	0.41
Right Knee				
Maximum Angle ($^{\circ}$)	115 \pm 6.0	115 \pm 5.0	114 \pm 7.0	0.80
Right Knee Angle at Contact ($^{\circ}$)	103 \pm 4.9	105 \pm 3.8	100 \pm 4.8*	0.05
Maximum Angular Velocity ($^{\circ}\cdot s^{-1}$)	474 \pm 276	474 \pm 183	474 \pm 368	0.99
Hip Segment Rotational Velocity				
Maximum Velocity ($^{\circ}\cdot s^{-1}$)	866.7 \pm 64.8	897.2 \pm 72.4	836.2 \pm 57.2 [#]	0.056
Time from Maximum to Ball Contact (s)	0.073 \pm 0.022	0.064 \pm 0.022	0.083 \pm 0.021	0.15
Left Hip				
Linear Velocity at Contact ($m\cdot s^{-1}$)	1.31 \pm 0.54	1.287 \pm 0.35	1.334 \pm 0.72	0.88
Maximum Linear Velocity ($m\cdot s^{-1}$)	5.35 \pm 1.6	4.978 \pm 1.8	5.728 \pm 1.5	0.41
Linear Displacement – in direction of ball travel (m)	0.16 \pm 0.03	0.16 \pm 0.04	0.15 \pm 0.02	0.38
Right Hip				
Linear Velocity at Contact ($m\cdot s^{-1}$)	1.78 \pm 0.67	1.940 \pm 0.78	1.617 \pm 0.57	0.39
Maximum Linear Velocity ($m\cdot s^{-1}$)	6.21 \pm 1.6	6.191 \pm 1.3	6.236 \pm 2.0	0.96
Linear Displacement – in direction of ball travel (m)	0.25 \pm 0.07	0.26 \pm 0.06	0.24 \pm 0.08	0.53
Stride				
Stride Length as a % of hip width (%)	24.46 \pm 16.2	21.12 \pm 18.5	27.79 \pm 14.2	0.46
Lead Foot (Left) Height as a % of subject height (%)	7.30 \pm 2.8	7.22 \pm 2.2	7.38 \pm 3.5	0.92

* Significant at the 0.05 level. [#] Approached significance ($p = 0.056$).

4.3 Correlations between bat swing kinematics

In order to further assess the importance of various measures to hitting performance, a series of targeted correlations were calculated. Previous research has indicated that early front arm extension (Breen 1967) and hip rotation (Race 1961) are key performance characteristics of the swing. In addition, the literature also identifies the relationship between bat swing velocity and resultant ball velocity (Bryant et al. 1977; Crisco et al. 2002; Greenwald, Penna & Crisco 2001; Nicholls et al. 2003; Nicholls, Miller & Elliott 2006; Weyrich et al. 1989).

As expected, Pearson's correlation tests revealed significant relationships between bat swing velocities and resultant ball velocity (Table 4.5). Analysis showed that maximum left elbow angular velocity was related to bat linear velocity at contact and right hip velocity at contact (Table 4.6). No other swing kinematics correlated with bat swing velocity. Table 4.7 presents correlation data for the left and right hips. Left hip velocity at contact correlated with left knee angle at contact and left knee maximum angle ($p < 0.05$). Right hip velocity at contact was significantly related to left hip maximum velocity, left knee angle at contact, and maximum left knee angle (Table 4.7).

Table 4.5: Pearson's correlation data for the relationship between bat and ball variables (A = Maximum Bat Linear Velocity, B = Bat Linear Velocity at Contact, C = Maximum Ball Linear Velocity).

Relationship	r value
A vs. B	.928**
A vs. C	.784**
B vs. C	.816**

** Significant at the 0.01 level.

Table 4.6: Pearson's correlation data for left elbow kinematics.

	Left Elbow Maximum Angle	Left Elbow Angle at Contact	Maximum Left Elbow Angular Velocity
Bat Linear Velocity at Contact	.420	.353	.499*
Left Hip Velocity at Contact	-.102	.025	-.198
Right Hip Velocity at Contact	.124	.143	.482*
Left Elbow Maximum Angle		.967**	.506*
Left Elbow Angle at Contact	.967**		.482*
Maximum Left Elbow Angular Velocity	.506*	.482*	

* Significant at the 0.05 level. ** Significant at the 0.01 level.

Table 4.7: Pearson's correlation data for hip kinematics.

	Left Hip Velocity at Contact	Left Hip Maximum Velocity	Right Hip Velocity at Contact	Right Hip Maximum Velocity
Bat Linear Velocity at Contact	-.076	-.093	0.050	-.070
Left Hip Maximum Velocity	.028		.520*	.397
Right Hip Maximum Velocity	.342	.397	.220	
Left Knee Angle at Contact	.498*	-.232	-.538*	.012
Left Knee Maximum Angle	.498*	-.240	-.540*	.012

* Significant at the 0.05 level.

4.4 Manipulating Bat Mass

Bat swing and resultant ball velocities for different bat masses are presented in Figure 4.1. Significant differences were found for both maximum bat swing and ball velocity. For maximum bat swing velocity, trials using Bat₁ elicited a mean speed of $36.0 \pm 3.2 \text{ m}\cdot\text{s}^{-1}$. This was significantly higher ($p < 0.01$) than the Bat₃ mean ($34.4 \pm 3.5 \text{ m}\cdot\text{s}^{-1}$). Resultant ball velocity was also significantly higher ($p < 0.05$) for Bat₁ ($38.4 \pm 3.1 \text{ m}\cdot\text{s}^{-1}$) compared to Bat₃ ($36.3 \pm 3.1 \text{ m}\cdot\text{s}^{-1}$).

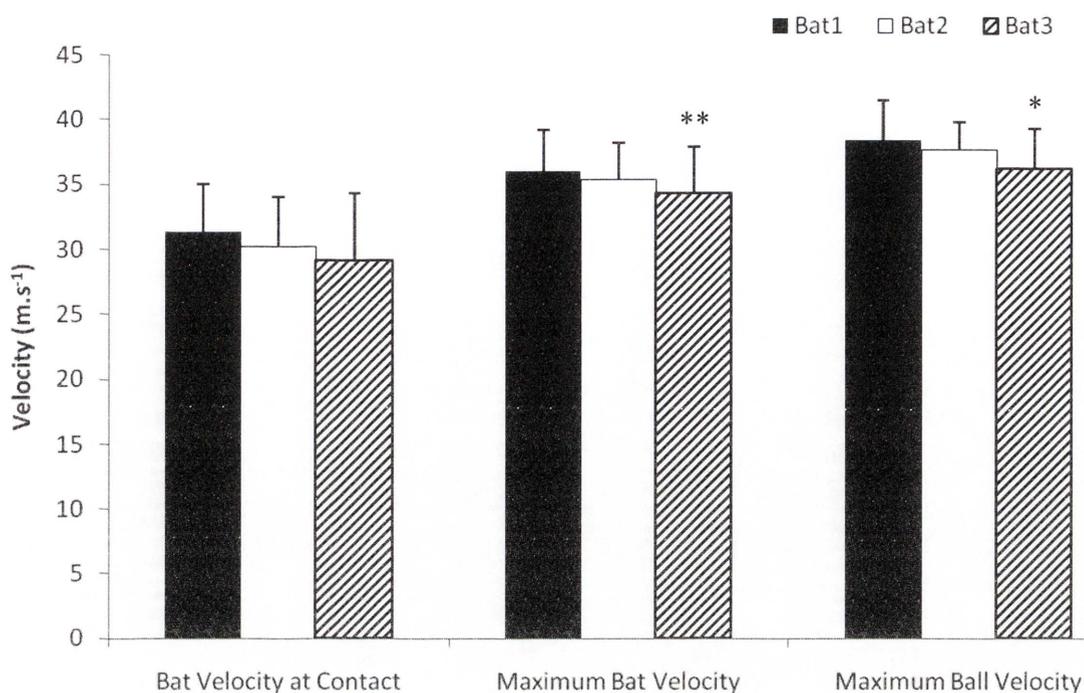


Figure 4.1 – Bat swing velocities (+ SD) and resultant ball velocity (+ SD) between bats. * Significantly different from Bat₁ ($p < 0.05$). ** Significantly different from Bat₁ ($p < 0.01$). (Bat₁ = 0.795kg, Bat₂ = 0.847kg, Bat₃ = 0.943kg).

Selected kinematics for the hip joints are shown in Figure 4.2. Left and right hip velocities at contact showed no significant differences. Left hip maximum velocity was significantly ($p < 0.01$) different between Bat₁ ($4.9 \pm 1.6 \text{ m}\cdot\text{s}^{-1}$) and Bat₃ ($6.9 \pm 1.5 \text{ m}\cdot\text{s}^{-1}$). There was also a significant difference ($p < 0.05$) between Bat₂ ($5.6 \pm 1.5 \text{ m}\cdot\text{s}^{-1}$) and Bat₃. Furthermore, maximum velocity of the right hip was significantly different between the three bats. Bat₃ ($5.4 \pm 1.5 \text{ m}\cdot\text{s}^{-1}$) was significantly lower ($p < 0.01$) as compared to Bat₁ ($6.5 \pm 1.6 \text{ m}\cdot\text{s}^{-1}$) and Bat₂ ($6.4 \pm 1.6 \text{ m}\cdot\text{s}^{-1}$).

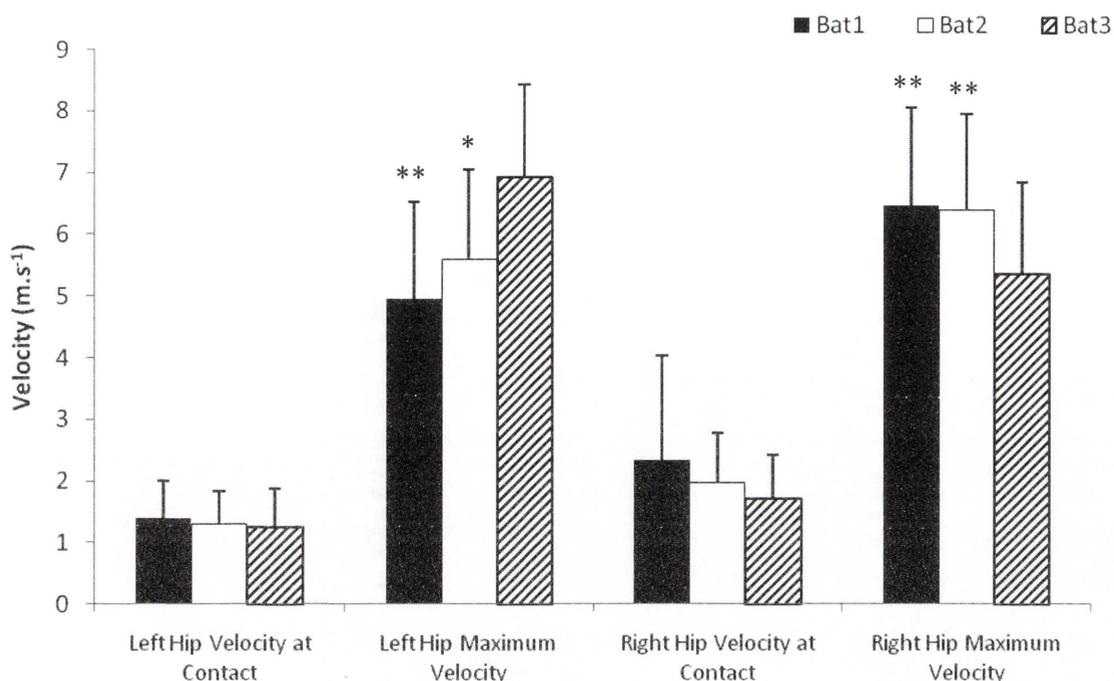


Figure 4.2 – Left and right hip velocities (+ SD) for each bat. * Significantly different from Bat₃ ($p < 0.05$). ** Significantly different from Bat₃ ($p < 0.01$). (Mass for each bat – Bat₁ = 0.795kg, Bat₂ = 0.847kg, Bat₃ = 0.943kg).

The means for selected bat swing kinematics are presented in Table 4.8. Repeated measures ANOVA showed that using Bat₁ produced significantly less (24.4%) head movement as compared to Bat₃. No other kinematic variables presented in Table 4.8 showed significant differences. Although not significant, it was noted that swing duration increased gradually with increases in bat mass and that left foot height off ground (as a percentage of subject height) decreased as bat mass increased.

Table 4.8: Kinematic comparisons between bats of different mass. Data is mean \pm SD.

Kinematic Variable	Bat ₁	Bat ₂	Bat ₃
Swing Duration (s)	0.259 \pm 0.05	0.268 \pm 0.05	0.277 \pm 0.05
Head Movement (m)	0.078 \pm 0.06	0.085 \pm 0.06	0.097 \pm 0.07*
Left Elbow			
-Maximum Angle ($^{\circ}$)	148 \pm 14.5	146 \pm 12.2	145 \pm 14.2
-Angle at Contact ($^{\circ}$)	147 \pm 15.0	145 \pm 13.8	143 \pm 15.4
-Maximum Angular Velocity ($^{\circ}\cdot\text{s}^{-1}$)	932 \pm 267.8	893 \pm 272.6	973 \pm 314.7
Right Elbow			
-Maximum Angle ($^{\circ}$)	134 \pm 11.4	134 \pm 10.3	131 \pm 9.9
-Angle at Contact ($^{\circ}$)	132 \pm 12.1	133 \pm 11.9	131 \pm 10.6
-Maximum Angular Velocity ($^{\circ}\cdot\text{s}^{-1}$)	2077 \pm 562.6	1950 \pm 475.8	1833 \pm 401.7
Lower Body			
Left Knee Angle at Contact ($^{\circ}$)	130 \pm 10.6	131 \pm 11.2	129 \pm 10.7
Right Knee Angle at Contact ($^{\circ}$)	103 \pm 6.2	103 \pm 5.0	102 \pm 5.1
Stride Length as a % of hip width (%)	23.97 \pm 18.5	22.86 \pm 16.6	24.70 \pm 19.1
Lead Foot (Left) Height as a % of subject height (%)	7.42 \pm 3.3	7.13 \pm 2.5	7.05 \pm 2.8

*Significantly different ($p < .05$) from Bat₁.

4.5 Summary of Key Results

Relatively Good vs. Relatively Poor Hitters:

1. The better batters recorded significantly higher maximum bat swing velocity, which resulted in significantly higher maximum resultant ball velocity.
2. Better batters had a greater maximum left elbow maximum angular velocity.
3. Right knee angle at ball contact was significantly higher amongst better hitters.

Swing Kinematics Correlation Data:

1. A significant, yet moderate, relationship occurred between maximum left elbow angular velocity and bat swing velocity at contact.
2. Right hip velocity at contact and left elbow maximum angular velocity displayed a significant correlation, although only indicating a moderate relationship.

Differences between bat masses:

1. Subjects were able to swing a light bat (Bat₁) significantly faster compared to a heavy bat (Bat₃).
2. Resultant ball velocity was significantly higher hitting with a light bat (Bat₁) compared to hitting with a heavy bat (Bat₃).
3. Batters produced significantly higher left hip maximum velocity when swinging a heavy bat (Bat₃) compared to swinging Bat₁ and Bat₂.

4. Batters produced significantly lower right hip maximum velocity when swinging a heavy bat (Bat₃) compared to swinging Bat₁ and Bat₂.
5. Head movement while hitting with a light bat (Bat₁) was lower than when using the heavy bat (Bat₃).

CHAPTER 5

DISCUSSION

5.1 Overview

It has been well documented that specific weighted implement training for baseball hitting is a successful modality when trying to improve bat swing velocity (DeRenne et al. 1995; DeRenne et al. 1992; DeRenne & Okasaki 1983; Southard & Groomer 2003; Szymanski 1998; Szymanski, Derenne & Spaniol 2009). However the contributory factors to such an increase have received little review, with only limited mention to key characteristics that make up the swing, which include; hip rotation, quick wrist action, lead forearm extension, stride length, and segmental timing (Breen 1967; Race 1961; Welch et al. 1995).

With these swing characteristics in mind, the aim of the cross-sectional research conducted was to specifically examine the impact of bats of varying mass on bat swing kinematics and observe differences between hitters of varying ability. It was hypothesized that there would be no significant biomechanical changes in swing technique, with bats of various mass. Further, it was hypothesized that there would be significant kinematic differences between hitters of relatively good and relatively poor ability. Once this was established, it permitted the examination of the impact of playing ability and bat mass on swing kinematics. Each will be examined below.

5.2 Relatively Good vs. Relatively Poor Hitters

Previous researchers have noted that bat swing velocity is of great importance for baseball hitters (DeRenne et al. 1995; Hughes, Lyons & Mayo 2004; Otsuji, Abe & Kinoshita 2002; Sergio & Boatwright 1993; Southard & Groomer 2003; Szymanski, Derenne & Spaniol 2009). A greater bat speed will allow the batter to see the pitch for longer before committing to a swing (Szymanski 1998) and produce greater resultant ball velocity (Fleisig et al. 2002; Lund & Heefner 2005). The current study has shown that good hitters produce higher maximum bat swing velocities compared to relatively poor hitters, thus supporting the notion that bat speed is a significant characteristic crucial to the baseball swing. Importantly, the resultant ball velocity was significantly higher amongst good hitters, resulting in part from the increased bat swing velocity (Table 4.2). The higher ball velocity has the potential to make fielding more difficult, thus increasing the batter's chance of reaching base. Sergio and Boatwright (1993) and DeRenne et al. (1995) reported that bat swing velocity can be increased through weighted implement training, although the specific kinematic mechanisms that lead to such change were not reported. Further research should employ similar training regimes, with additional examination of the kinematic changes (e.g. increased elbow angular velocity) within each hitter that occur during training.

It has been suggested that if maximum front arm extension occurs early in the swing it will allow for greater bat swing velocity, as the head of the bat is rotated about the wrist, rather than the handle being pulled around the bat head (Breen 1967). The

results of the current study showed that good hitters produced higher maximum left elbow (front arm) angular velocity during the swing ($991^{\circ}\cdot\text{s}^{-1}$ vs. $729^{\circ}\cdot\text{s}^{-1}$). Breen (1967) stated that a higher angular velocity of the front arm would lead to the hitter attaining maximum front arm extension earlier in the swing. However, further analysis of the current data showed that the spatial characteristics of peak angular velocity in the lead elbow did not differ between the two groups. More recently, Escamilla et al. (2009) showed differences in left elbow extension angular velocity between youth and adult hitters, with adult hitters achieving higher velocities ($752^{\circ}\cdot\text{s}^{-1}$ vs. $598^{\circ}\cdot\text{s}^{-1}$). It is plausible in this research that differences between the adult and youth hitters may be due to variance in strength, power and possibly technique. In the current study, muscular strength was not assessed however both groups were of similar body mass and height (Table 4.1). Therefore, it is postulated that the difference in the maximal angular velocity of the lead elbow may be due to more efficient application of technique through the summation of angular velocities (Putnam 1993).

Supporting this reasoning, further analysis of the current data showed a significant correlation between maximum bat swing velocity and left elbow maximum angular velocity ($r = 0.5$), which indicates that this facet accounts for 25% of the variance of maximum bat swing velocity. Collectively the results of the current and previous research indicate that the characteristics of the lead elbow portrayed in baseball hitting are crucial to the generation of high bat swing velocity and successful hitting. Future research should identify whether various training regimes, in particular those focusing on lead arm kinematics, are able to improve a hitter's bat swing velocity

and batting performance. This research should also examine what other factors make up the remaining variance in maximum bat swing velocity.

Biomechanical data presented by Welch et al. (1995) revealed that the right leg (rear leg) of professional hitters, at bat/ball contact was 135 degrees and loaded with approximately 16% of body weight. In the current study, good hitters had a larger knee angle compared to poor hitters, indicating a straighter leg at bat contact (106° vs. 100°). The preceding actions of the rear leg, before bat/ball contact, appear important to the success of the overall swing. It is hypothesised that the straighter back leg at ball contact reflects the ability of a hitter to transfer momentum from the lower body effectively. Specifically, a straighter back leg may lead to increased hip rotation, thus permitting a greater force production through the trunk, arms and bat, potentially leading to a higher bat swing velocity.

Early cinematographic analysis of the baseball swing in professional hitters indicated that hip rotation was a key characteristic to effective hitting (Race 1961). However, in the current study there was no difference in left or right linear hip velocity between good and poor hitters. Furthermore the translation of the hips (in the x-direction) was statistically equivalent between groups (Table 4.4). In contrast, the 7% difference in angular hip segment velocity between groups in the current study approached significance ($p=0.056$, Table 4.4). These findings suggest that good hitters generate a larger angular velocity at the hip which presumably enables a higher bat swing velocity. Thus, it is postulated that it is the magnitude of the angular hip segment velocity, not linear hip velocity that is a requirement for a high

bat swing velocity. Indeed, in contrast to the peak angular velocity data, there were no differences in the timing (relative to bat contact) of either maximum elbow or hip segment angular velocity (Table 4.3 and 4.4), indicating that the spatial characteristics of the swing were similar between groups. Welch et al. (1995) reported that hip rotation is an important component of the swing, allowing for the development of trunk preload such that the musculature of the trunk and upper extremity can contribute effectively to bat swing velocity.

No differences were found between levels of hitters for swing duration and head movement. Escamilla et al. (2009) reported significant differences in swing duration between hitters of varying age, with the stride phase providing the greatest impact on total swing time. The authors did note that the maturation of the older hitters may have resulted in size and strength advantages and thus were able to generate greater velocities. It is noted that a further breakdown (into phases) of the current study's swing may have found differences between good and poor hitters, however, such an analysis was beyond the scope of this project. Race (1961) reported that the movements of the head are vital to effective hitting. Specifically, amongst 17 elite hitters, only one raised their head prior to contact whilst the others lowered. The current study found no differences in head movement between hitters of varying skill, though it should be noted that all hitters tended to lower their head before contact (average vertical movement down of $0.087 \pm 0.07\text{m}$), supporting Race's (1961) earlier idea's on head movements.

In conclusion, for the selected kinematic variables in the current study, both similarities and differences occurred between good and poor hitters. Linear parameters, such as swing duration, head movement, stride length (as a percentage of hip width) and hip velocities displayed similarities when the two groups were compared. In contrast, differences were found between groups, for maximum bat swing velocity (and consequently ball velocity), left elbow maximum angular velocity and right knee angle at ball contact. Identifying bat swing characteristics crucial to successful hitting is essential and should be encouraged in future research, as it will allow both biomechanists and coaches to enhance baseball training methods to improve the baseball swing and further help in the discrimination between elite and sub-elite hitters.

5.3 Manipulating Bat Mass

There has been an abundance of literature examining the effect of swinging various weighted bats before swinging a regulation bat (DeRenne 1982, 1987, 1991; DeRenne et al. 1995; DeRenne et al. 1992; DeRenne & Okasaki 1983; Otsuji, Abe & Kinoshita 2002; Sergio & Boatwright 1993; Southard & Groomer 2003; Szymanski 1998; Szymanski, Derenne & Spaniol 2009). However, none of the research reported on the swing kinematics that occurred during training or warm-up. The current study aimed to provide relevant kinematic information that would most likely resemble swing patterns displayed in previous research methods.

As mentioned earlier in this chapter, Sego and Boatwright (1993) and DeRenne et al. (1995) reported that longitudinal training using bats of varying mass can lead to an increase in bat swing velocity, however specific changes in bat swing kinematics were not reported. The current study has shown that when using a light bat (0.795 kg) sub-elite hitters produce significantly higher maximum bat swing velocities when compared to a heavy bat (0.943 kg) (Figure 4.1). Furthermore, it was found that resultant ball velocity was higher when using a light bat compared to a heavy bat ($38.4 \text{ m}\cdot\text{s}^{-1}$ vs. $36.3 \text{ m}\cdot\text{s}^{-1}$), a direct relationship with maximum bat swing velocity ($r = .78$). Thus, it would be more beneficial for hitters to use the lighter bat, which allows for greater biomechanical control during the swing, in turn resulting in better bat/ball contact.

Another impact from increased bat velocity is decreased swing time (calculated from similar starting points). A decrease in swing time will allow for the hitter to see the pitch for longer (Szymanski 1998), thus increasing decision time and improving performance when determining whether or not to hit the ball. While swing duration was not significantly different between bats in the current study, a trend was present that was consistent with the change in contact and maximum bat swing velocities. Swing time increased 7% between the light and heavy bats, suggesting it would be more efficient swinging with a lighter bat from the perspective of seeing the ball for longer. This improvement may not result in further or faster hits, but rather better plate appearances for the hitter.

Although Breen (1967) reported that front arm extension was crucial to successful baseball hitting, and that significant differences occurred between young and old hitters' maximum left elbow angular velocity (Escamilla et al. 2009), no significant differences were found in the current study for left elbow swing kinematics when using bats of varying mass. While there was a trend for hitters to have a larger angle at contact when using a lighter bat, it cannot be concluded that this difference has a significant effect on bat swing velocity. Interesting there was a trend between bats for right elbow maximum angular velocity with the light bat producing higher velocities (13%) than the heavy bat. Future research should investigate both elbows swing kinematics overtime and how select variables may change with training.

A relationship exists between bat mass and maximum hip velocity which could be a potential mechanism for underlying training effects previously noted (DeRenne et al. 1995; Sergo & Boatwright 1993). The results indicated that the left hip moved 40% faster when using the heaviest bat compared to the light bat. The heavier the bat becomes, the harder it makes for the hitter to get the bat head to the ball, creating the effect of bat lag. To accommodate for this occurrence, it is possible that the lead hip moves faster to pull the upper body around, with the intent of executing a more effective swing. Thus, this change in speed of the left hip could be the mechanism by which bat swing velocity increases after performing weighted implement training, as faster hips could lead to a greater transfer of momentum (from hips through to bat) when returning to a standard game bat.

The level of the head is critical during hitting as any alteration will require adjustments by the eyes and muscles coordinating the movement (Race 1961). This study has shown that changing bat mass can significantly affect vertical movement of the head, which would consequently have a negative impact on batting performance. More specifically, as bat mass increases the vertical movement of the head is increased (24% in the current study) thus affecting the coordination of the swing and could possibly be one of the kinematic variables that contributes to decreased bat swing velocity in heavier bats.

During the load phase of the swing, a hitter will generally take their lead foot off the ground, with the purpose of building potential energy. In turn, the hitter's intent is to effectively transfer this energy through the body's segments and to the bat. When a hitter takes their lead foot off the ground their centre of gravity moves away from the ball and a greater concentration of body weight is shifted onto the rear leg (Lefebvre 1983). Although not significant this study shows that there was a trend for the lead leg height off the ground as a percentage of body height to decrease as bat mass increased. This finding suggests that as there is already an increased load present when a heavier bat is used (combination of subject and bat masses), the hitter spends less time loading the rear leg as a similar force is already present, similar to that of the lighter bats. However, this impacts bat swing velocity negatively as a greater momentum is needed to generate higher bat speeds in heavier bats.

5.4 Summary

The current project had two primary purposes; to identify baseball swing kinematics between hitters of varying ability and to identify biomechanical differences in the swing when using bats of varying mass. Furthermore the study provided significant correlations between particular swing kinematic variables.

The results demonstrated that within the limitations of the study, kinematic differences occur between hitters of varying skill. Most significantly, good hitters have a higher maximum bat swing velocity, greater maximum left elbow angular velocity and a greater right knee angle at contact. In addition, the major distinguishing kinematic differences between bats of different mass included maximum bat swing velocity (faster in lighter bats), maximum linear hip velocity, swing duration (shorter in lighter bats) and vertical head position (reduced movement in lighter bats).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Overview

The research undertaken in the current study examined the kinematic differences of the baseball swing between relatively good and relatively poor hitters. Additionally, the study examined the effects of bat mass on bat swing kinematics. A sub-elite group of hitters was selected and ranked according to a novel coaches rating and batting average, which deemed them to be either relatively good or poor hitters. The outcome measures for the cross-sectional investigation consisted of bat swing velocity, resultant ball velocity, joint angles, joint velocities, joint angular velocities, and movement responses of the head and lead foot.

6.2 Summary of Major Findings and Conclusions

Within the limitations of the research, the major findings, practical implications and conclusions of these included:

- As hypothesized, there were differences in swing kinematics between hitters of relatively good and relatively poor ability. Good hitters recorded superior maximum bat swing velocity in comparison to relatively poor hitters. This may lead to reduced swing duration, which presumably results in more time to see and react to the pitch, producing better hitting performance. Maximum resultant ball velocity was greater in relatively good hitters, in part a reflection of maximum bat swing velocity. An increased ball velocity can result in the ball travelling

further and possibly make it harder for the fielder to field the ball. It is concluded that maximum bat swing velocity is a significant performance indicator in baseball hitters.

- The relationship between left elbow maximum angular velocity and bat velocity at contact was highlighted in the current study, with left elbow maximum angular velocity accounting for a significant amount (25%) of the variance in hitting performance. In addition, left elbow maximum angular velocity was higher amongst good hitters compared to relatively poor hitters. It is clear that this component of the swing has a direct impact on bat swing velocity and helps to determine skill level amongst baseball hitters.
- Differences were displayed between good and poor hitters in the current study for right knee angle at ball contact, with relatively good hitters demonstrating a larger knee angles at contact. It is hypothesised that this larger angle may represent a more efficient use of the kinetic link principle and hence a greater transfer of momentum is witnessed from the lower body to the arms, and finally to the bat.
- The hypothesis, that there would be no changes in the kinematics of baseball bat swing technique when using bats of various mass, was disproven in the current study. Maximum bat swing velocity was significantly different when using bats of different mass in the current study. These findings highlight using a lighter bat

in order to achieve a faster swing. This study also showed that using a lighter bat will also result in a greater maximum resultant ball velocity.

- Vertical head movement was significantly reduced when using a lighter bat compared to a heavy bat. This finding is of great benefit for hitters, as changing eye level would potentially reduce hitting performance whilst tracking the pitch. Therefore, it is recommended that hitters choose a bat mass that will minimise any vertical head movement, to improve performance.
- Manipulating bat mass has an effect on the maximum linear velocity of the hips during the swing. As bat mass increases the left hip moves significantly faster and as the bat gets lighter the right hip moves significantly faster. If the left hip is moving faster (when using heavier bats) it will cause the hips to open up during the swing and possibly result in poor bat/ball contact and deteriorated batting performance.

6.3 Directions for future research

The research undertaken in the current study revealed numerous areas for future research. Based in the results and mechanisms associated with these findings, it is proposed that research is required to address the following issues:

- As the subjects in the current study all came from a homogenous baseball population (NSW Major League), it is possible that differences in skill level were not great enough to elicit other notable differences in swing characteristics that may be important. Future research should examine swing kinematics between two populations with a notably large skill difference (e.g. professionals vs. amateurs). This would permit a more appropriate analysis of swing kinematics, determining differences between good and poor hitters.
- The results of the present study suggest that there is a relationship between maximum bat swing velocity and left elbow maximum angular velocity in baseball hitters. To further explore this relationship, it is important to understand that the baseball swing is made up of various components and more importantly the sequential timing of these components. It is recommended that future research investigates the timing sequence of joint variables in detail, along with their relationship with maximum bat swing velocity.
- The current study analysed primarily linear kinematics of the swing. Further research should consider joint rotations and their contributions to swing performance.
- Some literature has indicated that a hitter's strength may be a variable that affects maximum bat swing velocity, rather than just technique. Therefore, a study that employs a way of measuring an individual's strength in collaboration with swing kinematics would be beneficial. A detailed examination of the relationship

between strength and bat swing kinematics may identify specific strength characteristics that need to be a focus for hitters to increase/improve performance.

- Training studies have previously been conducted with the purpose of increasing bat swing velocity. Future research should employ a similar rationale but examine the specific swing kinematics that change over a given period of time and determine whether technique with a heavier bat improves over time. This would allow coaches to focus more narrowly on certain swing characteristics, with the intention of improving performance.

REFERENCE LIST

1. Adair, R. 1995, 'The physics of baseball', *Physics Today*, vol. 48, no. 5, pp. 26-31.
2. Almasbakk, B. & Hoff, J. 1996, 'Coordination, the determinant of velocity specificity?' *Journal of Applied Physiology*, vol. 80, no. 5, pp. 2046-2052.
3. Ashley, S. 1990, 'Getting good wood (or aluminium) on the ball', *Mechanical Engineering*, vol. 112, no. 10, pp. 40-47.
4. Australian Sports Commission 2002, *Participation in Exercise Recreation and Sport Annual Report 2002*, in Department of Communications Information Technology and the Arts (ed.) Australian Government, Canberra.
5. Australian Sports Commission 2009, *Participation in Exercise Recreation and Sport Annual Report 2009*, in Department of Communications Information Technology and the Arts (ed.) Australian Government, Canberra.
6. Bahill, T. & Karnavas, W. 1991, 'The ideal baseball bat', *New Scientist*, vol. 130, pp. 24-29.
7. Behm, D. & Sale, D. 1993a, 'Intended rather than actual movement velocity determines velocity-specific training response', *Journal of Applied Physiology*, vol. 74, pp. 359-368.
8. Behm, D. & Sale, D. 1993b, 'Velocity specificity of resistance training', *Sports Medicine*, vol. 15, no. 6, pp. 374-388.

9. Bland, J. & Altman, D. 1995, 'Multiple significance tests: the Bonferroni method', *British Medical Journal*, vol. 310, no. 6973, p. 170.
10. Breen, J. 1967, 'What makes a good hitter?' *J Health Physical Education and Recreation*, vol. 38, pp. 36-39.
11. Bryant, F., Burkett, L., Chen, S., Krahenbaul, G. & Lu, P. 1977, 'Dynamic and performance characteristics of baseball bats', *The Research Quarterly*, vol. 48, no. 3, pp. 505-509.
12. Clark, J. 1993, *A History of Australian Baseball*, Univeristy of Nebraska Press, Lincoln.
13. Cluck, B. 1993, *Play Batter Baseball: Winning techniques and strategies for coaches and players*, Contemporary Books, Lincolnwood.
14. Crisco, J.J., Greenwald, R.M., Blume, J.D. & Penna, L.H. 2002, 'Batting performance of wood and metal baseball bats', *Medicine and Science in Sports and Exercise*, vol. 34, no. 10, pp. 1675-1684.
15. Cronin, J., McNair, P. & Marshall, R. 2002, 'Is velocity-specific training important in improving functional performance?' *Journal of Sports Medicine and Physical Fitness*, vol. 42, no. 3, pp. 267-273.
16. DeRenne, C. 1982, 'Increasing bat velocity', *Athletic Journal*, pp. 28-31.

17. DeRenne, C. 1987, 'Implement weight training programs', *National Strength and Conditioning Association Journal*, vol. 9, no. 3, pp. 35-37.
18. DeRenne, C. 1991, 'The donut: does it improve bat velocity', *National Strength and Conditioning Association Journal*, vol. 13, no. 3, pp. 43-45.
19. DeRenne, C., Buxton, B., Hetzler, R. & Ho, K. 1995, 'Effects of weighted bat implement training on bat swing velocity', *Journal of Strength and Conditioning Research*, vol. 9, no. 4, pp. 247-250.
20. DeRenne, C., Ho, K., Hetzler, R. & Chai, D. 1992, 'Effects of warm up with various weighted implements on baseball bat swing velocity', *Journal of Applied Sports Science Research*, vol. 6, no. 4, pp. 214-218.
21. DeRenne, C. & Okasaki, E. 1983, 'Increasing bat velocity (part II)', *Athletic Journal*, vol. 63, no. 7, pp. 54-55.
22. Dun, S., Fleisig, G.S., Loftice, J., Kingsley, D. & Andrews, J.R. 2007, 'The relationship between age and baseball pitching kinematics in professional baseball pitchers', *Journal of Biomechanics*, vol. 40, no. 2, pp. 265-270.
23. Escamilla, R.F., Fleisig, G.S., DeRenne, C., Taylor, M.K., Moorman, I.I.I.C.T., Imamura, R., Barakatt, E. & Andrews, J.R. 2009, 'A Comparison of Age Level on Baseball Hitting Kinematics', *Journal of Applied Biomechanics*, vol. 25, no. 3, pp. 210-218.

24. Fleisig, G., Zheng, N., Stodden, D. & Andrews, J. 2002, 'Relationship between bat mass properties and bat velocity', *Sports Engineering*, vol. 5, pp. 1-8.
25. Garhammer, J. 1983, 'A kinesiological analysis of hitting a baseball', *National Strength and Conditioning Association Journal*, vol. 5, no. 2, pp. 70-71.
26. Greenwald, R., Penna, L. & Crisco, J. 2001, 'Differences in batted ball speed with wood and aluminum baseball bats: a batting cage study', *Journal of Applied Biomechanics*, vol. 17, pp. 241-252.
27. Hendee, S., Greenwald, R. & Crisco, J. 1998, 'Static and dynamic properties of various baseballs', *Journal of Applied Biomechanics*, vol. 14, pp. 390-400.
28. Hopkins, W.G., Marshall, S.W., Batterham, A.M. & Hanin, J. 2009, 'Progressive statistics for studies in sports medicine and exercise science', *Medicine and Science in Sports and Exercise*, vol. 41, no. 1, pp. 3-13.
29. Hughes, S., Lyons, B. & Mayo, J. 2004, 'Effect of grip strength and grip strengthening exercises on instantaneous bat velocity of collegiate baseball players', *Journal of Strength and Conditioning Research*, vol. 18, no. 2, pp. 298-301.
30. International Baseball Federation 2010, *IBAF World Rankings - June 2010*.

31. Kagan, D. 1990, 'The effects of coefficient of restitution on long fly balls', *American Journal of Physics*, vol. 58, no. 2, pp. 151-154.
32. Kanehisa, H. & Miyashita, M. 1983, 'Specificity of velocity in strength training', *European Journal of Applied Physiology*, vol. 52, pp. 104-106.
33. Kaneko, M., Fuchimoto, T. & Toji, H. 1983, 'Training effect of different loads on the force-velocity relationship and mechanical power output in human muscle', *Scandinavian Journal of Sports Science*, vol. 5, no. 2, pp. 50-55.
34. Kawamori, N. & Newton, R. 2006, 'Velocity specificity of resistance training: actual movement velocity versus intention to move explosively', *Strength and Conditioning Journal*, vol. 28, no. 2, pp. 86-91.
35. Kraemer, H. & Thiemann, S. 1987, *How many subjects? Statistical power analysis in research*, Sage, Newbury Park.
36. Lapchick, R., Ekiyor, B. & Ruiz, H. 2006, *The 2006 Racial and Gender Report Card: Major League Baseball*, University of Florida, Orlando.
37. Lefebvre, J. 1983, 'Hitting the baseball: let's understand the process', *National Strength and Conditioning Association Journal*, no. April-May, pp. 6-7, 70-71.

38. Lerner, K. & Lerner, B. 2007, 'Baseball', in, *World of Sports Science*, Thomson Gale, Farmington Hills, pp. 60-69.
39. Lund, R. & Heefner, D. 2005, 'Training the baseball hitter', *Journal of Physical Education Recreation and Dance*, vol. 76, no. 3, pp. 27-33.
40. Nathan, A. 2000, 'Dynamics of the baseball-bat collision', *American Journal of Physics*, vol. 68, no. 11, pp. 979-990.
41. Nathan, A., Russell, D. & Smith, L. 2004, 'The physics of the trampoline effect in baseball and softball bats', paper presented to the *5th International Conference on the Engineering of Sport*, University of California.
42. Nicholls, R., Elliott, B., Miller, K. & Koh, M. 2003, 'Bat kinematics in baseball: implications for ball exit velocity and player safety', *Journal of Applied Biomechanics*, vol. 19, pp. 283-294.
43. Nicholls, R., Miller, K. & Elliott, B. 2006, 'Numerical analysis of maximal bat performance in baseball', *Journal of Biomechanics*, vol. 39, no. 6, pp. 1001-1009.
44. Noble, L. & Eck, J. 1986, 'Effects of selected softball bat loading strategies on impact reaction impulse', *Medicine and Science in Sports and Exercise*, vol. 18, pp. 50-59.

45. Otsuji, T., Abe, M. & Kinoshita, H. 2002, 'After-effects of using a weighted bat on subsequent swing velocity and batters' perceptions of swing velocity and heaviness', *Perceptual Motor Skills*, vol. 94, no. 1, pp. 119-126.
46. Pereira, M. & Gomes, P. 2003, 'Movement velocity in resistance training', *Sports Medicine*, vol. 33, no. 6, pp. 427-438.
47. Perneger, T. 1998, 'What's wrong with Bonferroni adjustments', *British Medical Journal*, vol. 316, no. 7139, pp. 1236-1238.
48. Putnam, C.A. 1993, 'Sequential motions of body segments in striking and throwing skills: descriptions and explanations', *Journal of Biomechanics*, vol. 26 Suppl 1, pp. 125-135.
49. Race, D. 1961, 'A cinematographic and mechanical analysis of the external movements involved in hitting a baseball effectively', *Research Quarterly*, vol. 35, pp. 433-437.
50. Russo, J. & Landolphi, D. 1998, *The fundamentals of coaching and playing baseball*, Allyn and Bacon, Needham Heights.
51. Sawicki, G., Hubbard, M. & Stronge, W. 2003, 'How to hit home runs: optimum baseball bat swing parameters for maximum range trajectories', *American Journal of Physics*, vol. 71, no. 11, pp. 1152-1162.

52. Sergo, C. & Boatwright, D. 1993, 'Training methods using various weighted bats and the effects on bat velocity', *Journal of Strength and Conditioning Research*, vol. 7, no. 2, pp. 115-117.
53. Smith, L. 2001, 'Evaluating baseball bat performance', *Sports Engineering*, vol. 4, pp. 205-214.
54. Southard, D. & Groomer, L. 2003, 'Warm-up with baseball bats of varying moments of inertia: effect on bat velocity and swing pattern', *Research Quarterly for Exercise and Sport*, vol. 74, no. 3, pp. 270-276.
55. Szymanski, D. 1998, 'The effect of various weighted bats on bat velocity - literature review', *Strength and Conditioning Journal*, vol. 20, no. 3, pp. 8-11.
56. Szymanski, D., McIntyre, J., Szymanski, J., Molloy, J., Madsen, N. & Pascoe, D. 2006, 'Effect of wrist and forearm training on linear bat-end, center of percussion, and hand velocities and on time to ball contact of high school baseball players', *Journal of Strength and Conditioning Research*, vol. 20, no. 1, pp. 231-240.
57. Szymanski, D.J., Derenne, C. & Spaniol, F.J. 2009, 'Contributing factors for increased bat swing velocity', *Journal of Strength and Conditioning Research*, vol. 23, no. 4, pp. 1338-1352.

58. Tabuchi, N., Matsuo, T. & Hashizume, K. 2007, 'Bat speed, trajectory, and timing for collegiate baseball batters hitting a stationary ball', *Sports Biomechanics*, vol. 6, no. 1, pp. 17-30.
59. Welch, C., Banks, S., Cook, F. & Draovitch, P. 1995, 'Hitting a baseball: a biomechanical description', *Journal of Orthopaedic and Sports Physical Therapy*, vol. 22, no. 5, pp. 193-201.
60. Weyrich, A., Messier, S., Ruhmann, B. & Berry, M. 1989, 'Effects of bat composition, grip firmness, and impact location on postimpact ball velocity', *Medicine and Science in Sports and Exercise*, vol. 21, no. 2, pp. 199-205.
61. Williams, J., Trinklein, F., Metcalfe, H. & Lefler, R. 1972, *Modern Physics*, Holt, Rinehart, & Winston, Sydney.
62. Wilson, G., Newton, R., Murphy, A. & Humphries, B. 1993, 'The optimal training load for the development of dynamic athletic performance', *Medicine and Science in Sports and Exercise*, vol. 25, no. 11, pp. 1279-1286.

APPENDICES

Appendix 1

Informed Consent Form

INFORMED CONSENT FORM



I, _____ agree to participate in the research project "**The effects of weighted implements on bat swing velocity and bat swing biomechanics**" being conducted by Brendan Inkster, Human Movement student, School of Leisure, Sport and Tourism, (Phone: _____) of the University of Technology, Sydney.

I understand that the purpose of this study is to evaluate the effects that different weighted bats have on bat swing velocity and bat swing biomechanics.

I understand that my participation in this research may involve up to 2 hours of my time, for one testing session. I also understand that there are possible risks of participating in this study. These possible risks are:

1. **Muscle Strains:** There is a minor risk of suffering a muscular strain during the tasks being completed during the study. As the testing involves maximal force production, it is important to warm-up prior to exercise and cool down at the completion. Leading up to the maximal efforts, you will perform activities that gradually build up your muscle temperature to ensure that injury risk is minimized.
2. **Muscle Soreness:** In the 48 hours after the testing, you may experience some muscle soreness. If you do experience excessive soreness please inform the chief investigator.
3. **Impact Injury:** There is a minor chance of being struck by a baseball. However, such risk will be minimised where the participant uses correct technique and obeys safety procedures.

I am aware that I can contact Brendan Inkster or their supervisor Dr Aron Murphy (Phone: 9514 5294) if I have any concerns about the research. I also understand that I am free to withdraw my participation from this research project at any time I wish and without giving a reason.

I understand that UTS attempts to ensure that the greatest of care will be taken by the researchers during the testing and training sessions. However, I acknowledge that UTS, its agents and employees will not be liable for any loss or damage arising directly or indirectly from these testing and training sessions. I acknowledge and accept that there are risks involved, including but not limited to discomfort, injury and, in extremely rare circumstances, death.

I acknowledge and accept that my participation is entirely voluntary, and that UTS has accepted my participation in good faith without express implied warranty. I agree that Brendan Inkster has answered all my questions fully and clearly.

I agree that the research data gathered from this project may be published in a form that does not identify me in any way.

Signed by _____ / /

Signed by (Parent or Guardian if under 18) _____ / /

Witnessed by _____ / /

NOTE:
This study has been approved by the University of Technology, Sydney Human Research Ethics Committee. If you have any complaints or reservations about any aspect of your participation in this research which you cannot resolve with the researcher, you may contact the Ethics Committee through the Research Ethics Officer, Ms Susanna Davis (ph: 02 9514 1279). Any complaint you make will be treated in confidence and investigated fully and you will be informed of the outcome.

Appendix 2

Pre-exercise Health Screen Questionnaire

Health Screen Questionnaire

To be completed prior to partaking in this study.

Name: _____ Age: _____ Gender: M F
 Phone (H): _____ Phone (M): _____
 Baseball Playing Position: _____
 Height: _____ Weight: _____ Today's Date: _____

Stage 1 - Known Diseases (Medical Conditions)

1. List the medications you take on a regular basis.

2. Do you have diabetes? No Yes
 - a) If yes, please indicate if it is insulin dependent diabetes mellitus (IDDM) or non-insulin dependent diabetes mellitus (NIDDM). IDDM NIDDM
 - b) If IDDM, for how many years have you had IDDM? _____ years
3. Have you had a stroke? No Yes
4. Has your doctor ever said you have heart trouble? No Yes
5. Do you take asthma medication? No Yes
6. Is there any other physical reason that prevents you from participating in an exercise program, (e.g., cancer, osteoporosis, severe arthritis, mental illness, thyroid, kidney, or liver disease)? No Yes

Stage 2 - Signs and Symptoms

7. Do you often have pains in your heart, chest, or surrounding areas, especially during exercise? No Yes
8. Do you often feel faint or have spells of severe dizziness during exercise? No Yes
9. Do you experience unusual fatigue or shortness of breath at rest or with mild exertion? No Yes
10. Have you had an attack of shortness of breath that came on after you stopped exercising? No Yes
11. Have you been awakened at night by an attack of shortness of breath? No Yes
12. Do you experience swelling or accumulation of fluid in or around your ankles? No Yes
13. Do you often get the feeling that your heart is beating faster, racing, or skipping beats, either at rest or during exercise? No Yes
14. Do you regularly get pains in your calves and lower legs during exercise which are not due to soreness or stiffness? No Yes
15. Has your doctor ever told you that you have a heart murmur? No Yes

Stage 3 - Cardiac Risk Factors

16. Do you smoke cigarettes on a daily basis, or have you quit smoking within the past two years? **No** **Yes**

If yes, how many cigarettes per day do you smoke (or did you smoke in the past two years)? _____ per day

17. Has your doctor ever told you that you have high blood pressure? **No** **Yes**

18. Has your father, mother, brother, or sister had a heart attack or suffered from a cardiovascular disease before the age of 65? **No** **Yes**

If yes,
a) Was the relative male or female? _____

b) At what age did he or she suffer the stroke or heart attack? _____

c) Did this person die suddenly as a result of the stroke or heart attack? _____

Enter blood pressure and blood lipid values:
19. What is your systolic blood pressure? _____ mmHg

20. What is your diastolic blood pressure? _____ mmHg

21. What is your serum cholesterol level? _____ mmol/L or mg/dL

22. What is your serum HDL level? _____ mmol/L or mg/dL

23. What is your serum triglyceride level? _____ mmol/L or mg/dL

Stage 4 - Exercise Intentions

24. Does your job involve sitting for a large part of the day? **No** **Yes**

25. What are your current activity patterns?
a) Frequency: _____ exercise sessions per week
b) Intensity: Sedentary Moderate Vigorous
c) History: <3 months 3-12 months >12 months
d) Duration: _____ minutes per session

26. What types of exercises do you do?

Additional

27. Have you had any major joint surgery within the past 12 months? **No** **Yes**

28. If you are allergic to any medications, foods, or other substances, please name them.

29. List and describe any injuries, back problems, musculoskeletal abnormalities, areas of pain/discomfort, etc. Please give as much detail as possible.

Appendix 3

Identification of Biomechanical Variables

Swing Initiation - was determined as the instance bat swing velocity reached $1 \text{ m}\cdot\text{s}^{-1}$ and continued to increase rapidly within the proceeding 5 frames.

Bat/ball contact - was defined as the frame before the ball left the tee.

Swing duration was the total time between swing initiation and bat/ball contact.

Maximum angles and velocities presented in the current study are taken from this time period.

Elbow angle - was defined as the intersection of the shoulder to the elbow vector, and elbow to the wrist vector.

Knee angle - was defined as the intersection of the hip to the knee and knee to the ankle vectors.

Elbow and knee angles were defined as 180° when full extension was achieved.

Head movement - was noted as the head marker's maximum change in Z-direction throughout the swing duration.

Stride length - was calculated by taking the difference between the left ankle marker X-position prior to the foot leaving the ground and the left ankle marker X-position when the foot returned to the ground, and presented as a percentage of hip width.

Hip width - was the distance between the two iliac crest markers.

Lead foot height - was defined as the distance between the left ankle marker Z-position when the foot was in contact with the ground and the maximum Z-position when the foot was in the air.