CRITICAL PARAMETERS OF THE DELIVERY IN TEN PIN BOWLING

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Original Literary Work Declaration

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Abstract

This exploratory study examined the possible important parameters for high level bowlers in three main areas - physical attribute, kinematics and movement variability. Consideration of the 'critical' parameters was made by looking at the variables that best distinguished the elite from the semi-elite bowlers using the discriminant function analysis. The study had an applied perspective in terms of the applications of the results and findings. Elite and semi-elite bowlers were grouped by their bowling score average (BS_{ave}), with participants scoring 200 pin falls and above assigned to the elite group. A total of 18 elite bowlers (M=10, F=8; BS_{ave} 213.2±6.80), 12 semi-elite bowlers (M=7, F=5; BS_{ave} 181.3±9.36) and 33 sedentary university students (M=14, F=19) representing the normal population were recruited.

Ten anthropometric measurements and seven strength tests were conducted but there were no identifiable critical parameter of physical attributes for better bowlers as it was not possible to successfully distinguish between elite and semi-elite bowlers. However, differences were found when compared to the normal population, whereby the bowlers were heavier, had longer limbs, had stronger forearm internal rotation and arm flexion.

A four-camera, 100 Hz, video-based 3D motion capture system was utilised for technique analysis. A total of 43 discrete kinematic variables were gathered from the motion analysis, out of which it was concluded that the two bowling groups had similar kinematic patterns for the majority of segments, with the exception of the shoulder and elbow regions. Discriminant analysis revealed that there were three critical kinematic variables, which showed an estimated 76.7% success rate for cross-validated classification in distinguishing the elite and semi-elite bowlers.

From the discrete kinematic data, the within-subject inter-trial variability was also extracted to compare movement consistency. Consequently, 41 absolute variability variables were examined with a number of differences observed between the elite and semi-elite bowlers especially at the base (foot region) and the wrist, both of which are the most distal segments. The discriminant analysis highlighted four critical variability variables, with an estimated 76.7% success rate in distinguishing bowling playing level.

It was concluded that the critical parameters of delivery for good bowling performance were faster shoulder velocity at front foot strike, faster elbow velocity at release, lower wrist height at release, more consistent foot lateral position at front foot strike, more consistent wrist lateral position at release, more varied foot slide distance, and more varied wrist superior-inferior position at release.

Finally, as a consequence of the vast data gathered from this study, anthropometric and strength normative data, as well as kinematics and absolute variability measures for high level bowlers in Malaysia have been established and are readily available as a reference.

Abstrak

Penyelidikan awalan ini mengkaji parameter yang berkemungkinan penting bagi pemain boling prestasi tinggi, di dalam tiga bidang utama – sifat fizikal, kinematik dan variabiliti pergerakan. Pertimbangan untuk klasifikasi parameter 'kritikal' di buat berdasarkan kebolehan pembolehubah tersebut membezakan pemain elit berbanding pemain semi-elit, melalui hasil keputusan analisis fungsi pembezalayan. Penyelidikan ini mempunyai perspektif gunaan dalam soal aplikasi keputusan dan penemuan. Pemain boling elit dan semi-elit telah dipecahkan kepada dua kumpulan berdasarkan mata boling purata mereka (BS_{ave}), dimana peserta yang mempunyai 200 jatuhan pin dan ke atas diuntukkan sebagai golongan elit. Sejumlah 18 pemain boling elit (M=10, F=8; BS_{ave} 213.2±6.80), 12 pemain boling semi-elit (M=7, F=5; BS_{ave} 181.3±9.36) dan 33 pelajar universiti sedentari (M=14, F=19) mewakili populasi awam telah digunakan.

Sepuluh pengukuran anthropometrik dan tujuh ujian kekuatan telah dijalankan, tetapi tidak ada parameter sifat fizikal kritikal yang dapat dikenal pasti kerana hasil analisis fungsi pembezalayan tidak berjaya membezakan di antara pemain elit berbanding semi-elit. Bagaimanapun, perbezaan telah dikenal pasti apabila dibanding dengan populasi awam, di mana pemain-pemain boling di dapati lebih berat, mempunyai anggota badan yang lebih panjang, mempunyai kekuatan putaran internal lengan dan kekuatan fleksi siku yang lebih.

Bagi analisis teknik, sebuah system empat kamera, 100 Hz, penangkap-gerakan 3D berasaskan video telah digunakan. Sejumlah 43 pembolehubah kinematik diskrit telah dikumpul dari analisis pergerakan, dimana dapat disimpulkan bahawa kedua-dua kumpulan pemain mempunyai corak kinematik serupa bagi kebanyakkan anggota badan, dengan

pengecualian bagi kawasana bahu dan siku. Analisis pembezalayan mendedahkan bahawa terdapat tiga pembolehubah kinematik kritikal, yang menunjukkan anggaran 76.7% kadar kejayaan bagi klasifikasi pengesahan-silang dalam membezakan pemain boling elit dan semi-elit.

Daripada data kinematik diskrit pula, kebolehubahan antara-percubaan setiap peserta juga diekstrak keluar untuk membandingkan ketekalan pergerakan. Sejumlah 41 pembolehubah kebolehubahan mutlak telah diperiksa dan didapati terdapat beberapa perbezaan antara pemain boling elit dan semi-elit terutama di kawasan tapak (bahagian kaki) dan pergelangan tangan, yang mana kedua-duanya merupakan segmen paling distal. Analisis pembezalayan menunjukkan empat pembolehubah kebolehubahan kritikal, dengan anggaran 76.7% kadar kejayaan dalam membezakan tahap boling pemain.

Disimpulkan bahawa parameter kritikal untuk mencapai prestasi boling yang cemerlang adalah kelajuan bahu lebih tinggi ketika kaki depan mendarat, kelajuan fleksi siku lebih tinggi ketika melepaskan bola, kedudukan ketinggian pergelangan tangan lebih rendah ketika melepaskan bola, kedudukan sisi kaki yang lebih konsisten ketika kaki depan mendarat, kedudukan sisi pergelangan tangan yang lebih konsisten ketika melepaskan bola, jarak lunjuran kaki lebih berbeza-beza, dan kedudukan atas-bawah pergelangan tangan kedudukan sisi yang lebih berbeza.beza

Akhir kata, hasil daripada jumlah data luas yang didapati dari kajian ini, data normatif anthropometrik dan kekuatan, beserta data kinematik dan kebolehubahan mutlak pemain boling peringkat tinggi di Malaysia telah diwujudkan dan boleh diguna sebagai rujukan.

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List of Published Work Arising from this Thesis

1. Razman, R., Cheong, J. P. G., Wan Abas, W. A. B., & Abu Osman, N. A. (2012). Anthropometric and strength characteristics of ten pin bowlers with different playing abilities. *Biology of Sport, 29*, 33-38. (*ISI-Cited Publication*)

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4. Razman, R., Wan Abas, W. A. B., Abu Osman, N. A., & Cheong, J. P. G. (2011). Temporal characteristics of the final delivery phase in ten pin bowling and its relationship to performance. *Proceedings of the 5th Kuala Lumpur International Conferences on Biomedical Engineering,* pp. 222-224. Kuala Lumpur, Malaysia.

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CHAPTER ONE:
INTRODUCTION

Chapter 1: Introduction

The game of bowling had its earliest inception near 3200 BC in Egypt. In Europe, there are claims that it has been around in Germany since 300 BC and in England from the 1100's. The current form of bowling has its roots dating back the 16th century in the Netherlands. Throughout those years, bowling was enjoyed as a recreational game with the occasional competitive aspect fuelled by monetary bets. The first organised association established with the intention to form structured competition was inaugurated in 1926 while the FIQ (International Federation of Bowlers) was initiated as recently as 1952. From then on, domestic and international competitions began to appear.

In 1961, bowling was introduced into Malaysia when the first bowling centre was set up in Penang. Around 1965, the Malaysian Tenpin Bowling Congress (MTBC) was established. In 1970, Malaysia had its first international success with an eight out of nine gold medal haul at the Asian FIQ Championships in Hong Kong. Since then, Malaysia has had tremendous success with medals at the World Championships, World Cup, Commonwealth Games and Asian Games.

FIQ considers bowling a competitive technical sport. Although it may not be as physically demanding on the human body as certain other competitive sports, its demand on technical expertise and finesse is nearly second to none (Rypcinski, 2002). This is supported by the fact that bowling is included in multi-sport games such as the Commonwealth and Asian Games for many years now. Additionally, a majority of elite bowlers compete in a number a professionally run leagues around the world, not to mention the many open tournaments that offer generous amounts of prize money.

To underline the competitive nature of bowling and help its cause towards acceptance into the Olympics, FIQ went to the extent of commissioning a study to differentiate between elite and amateur bowlers (Johnson, 2002). Even though the results were only available on their website and had a rather biased view (as it was a commissioned study), the study highlighted the vast qualitative and quantitative difference in skill levels and execution between a good bowler and an average one. It had hoped to pave the way for more specific research on ten pin bowling skills. Prior to that, Thomas, Schlinker and Over (1996) had assessed psychological and psychomotor skills of bowlers and concluded that there were significant differences between skilled and less skilled bowlers.

1.1 The Sport of Ten Pin Bowling

Ten pin bowling is a sport in which a player (known as the "bowler") rolls a bowling ball down a wooden or synthetic lane with the objective of knocking down as many pins as possible. The 41.5-inch (1.05 m) wide, 60-foot (18.29 m) long lane is oiled (between 18 to 30 ml of oil) and has parallel ‘drains’ bordering along its length (known as gutters) to collect balls that are bowled way off-target (Figure 1.1).

There is a "foul line" at the front end of the lane. If any part of a bowler's body touches the lane side of this line after the ball is released, it is considered a "foul" and the preceding pin knock downs are not tallied. Behind the line there is an area approximately 15-feet (4.57 m) long used in the delivery approach to gain initial overall momentum before delivery. At the front, 18.29 m from the foul line, is where the lane ends.

For competitive bowling, the ball is made of a completely solid material and its weight distributed evenly. The circumference does not exceed 2.25 feet (0.686 m), while the weight

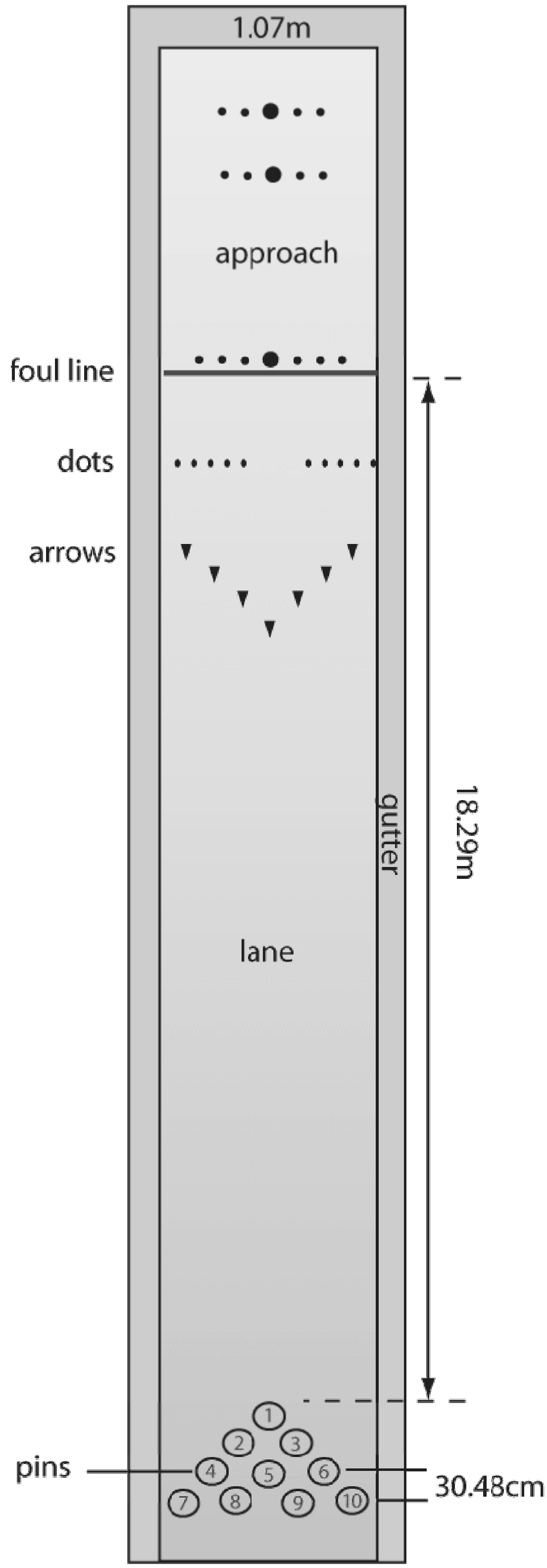


Figure 1.1: Bowling lane layout

does not exceed16 pounds (7.26 kg). It has a smooth surface over its entire circumference except for holes or indentations used for gripping the ball, holes or indentations made to bring the ball back into compliance with weight-distribution regulations, identification letters and numbers, and general wear from normal use. The design and technology in bowling evolved so dramatically over the past few years that the regulating bodies had to draw out explicit rules which involve stringent test and certification procedures (FIQ, 2010) that restrict certain characteristics of the ball such as the radius of gyration and hooking potential.

Meanwhile, a pin is 15-inches (38.1 cm) tall and about 4.7-inches (11.4 cm) wide at the "belly" of the pin, the point where a ball would make contact. The weight of a single pin is at least 3 pounds, 4 ounces (1.47 kg) and no more than 3 pounds, 10 ounces (1.64 kg). There are ten pins that are set into four rows which form an equilateral triangle with four pins on a side, also known as a Tetractys shape. There are four pins in the back row, then three, then two, and finally one in the front at the center of the lane (see Figure 1.2). For common terms of reference, the pins are numbered one through ten, starting with one in front, and ending with ten in the back to the right.

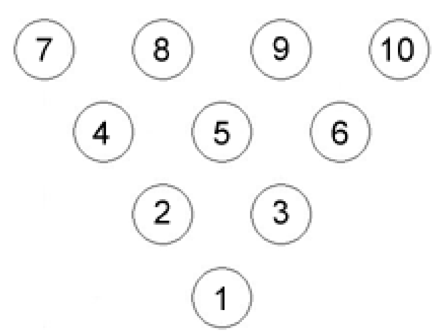


Figure 1.2: Standard pin arrangement

Each pin is set up 12 inches (30 cm) apart, measured from center to center. Due to the spacing of the pins and the size of the ball which is about 8.6 inches or 22 cm in diameter, it is impossible for the ball to contact every pin. Therefore, a precise measured shot is needed, which would result in a calculated reaction of pin hitting pin.

A bowler is allowed ten tries (frames) in a game in which to knock down pins, with each frame consisting of up to two deliveries. If the first ball rolled knocks down all ten pins (also referred to as a ‘strike’), the frame is completed. However, when there are pins left standing after the first ball, those that were knocked down are counted and removed. A second ball is rolled and if the remaining pins are knocked down, the term "spare" is used. If all ten pins were to fall with each first shot and also achieve strikes with each of the bonus balls in the tenth frame, it would then be considered a "perfect game" of 300 – which is the ultimate aim of every bowler. In a tournament, a competitive bowler will usually bowl six games a day and depending on their progress, would compete for between three to five consecutive days.

Generally there are two primary styles of rolling the ball down the lane. New players often play by rolling the ball straight, aiming for the 1-3 pocket for right-handed bowlers or the 1-2 pocket for left-handed bowlers. It has been acknowledged that to get the ideal shot to get the perfect strike, the ball will only touch pins 1, 3, 5 and 9 for a right-handed bowler with the rest of the pins falling due to pin-to-pin interaction. For this ideal shot to occur, the ball needs to enter the pocket at an angle of about 6 degrees from the first pin (from a line parallel to the gutter). Unfortunately it means that a ball that is thrown straight will need to be bowled from the next corresponding lane (explained in detail by Johnson, 1998), which is nearly an impossible task.

Therefore, more experienced bowlers will use a more precise technique to target the respective pockets. The ball path will be curved (hooked), whereby the ball starts out straight, and then curves towards the pocket. To produce a hook, the player needs to let go of the ball with a slightly different release technique and more wrist rotation. This will make the ball rotate about its axis with the spin of the ball producing friction with the lane surface and resulting in a curved path. The more the spin, the more 'hooked' the path will be.

The conventional bowling styles use either a 4 or 5-step approach beginning 8 to 16 feet (2.44 to 4.88 m) behind the foul line. Generally, a bowler starts by grasping the ball with two hands near the chest, and then they would initiate a backswing – termed as the 'pushaway'. Whilst continuing to take forward steps, the ball is swung back up to a point before being swung forward to generate forward momentum. Prior to releasing the ball, the bowler will take the last step and initiate a slide that will end before the foul line. The ball is then released at the end of the slide. Figure 1.3 illustrates the bowling action described above.

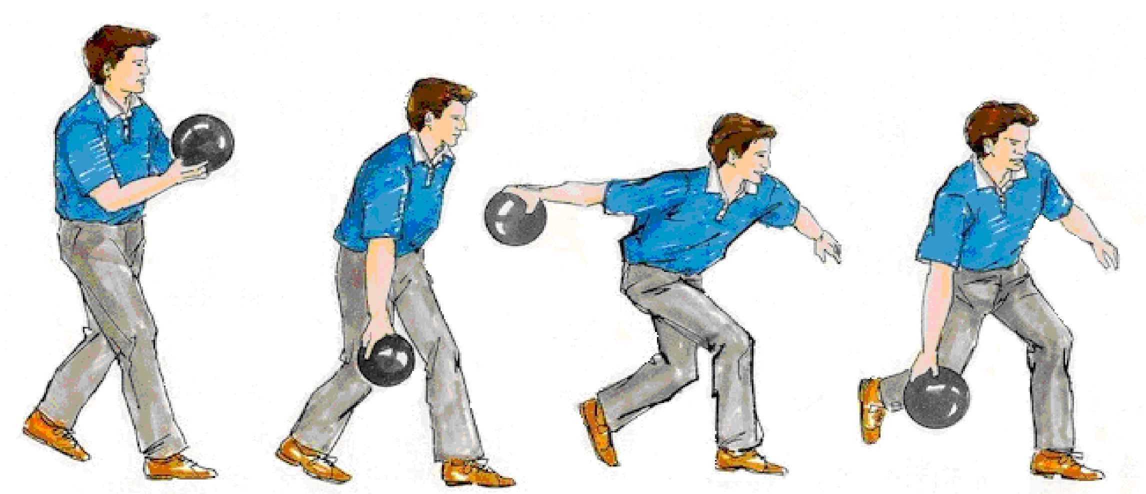


Figure 1.3: Sequence of a bowling delivery

There are many different skill components in ten pin bowling and it can be looked at in many different ways. The most common way of looking at it is to categorise the components according to the phases of the bowling action (Strickland, 1996). The phases for the components are listed in the following order:

- Delivery – Stance, pushaway, back swing, forward swing, slide, ball release.
- Ball Travel – Ball flight, ball roll/spin and the resulting ball path.
- Ball to Pin Contact – First contact, resulting ball-to-pin and pin-to-pin interaction

1.2 Statement of the Problem

Published academic literature on ten pin bowling is surprisingly scarce for such a popular sport. Even then, those that are available are either related only to psychological aspects (Thomas, Schlinker, & Over, 1996), or physiological aspects (Tan, Aziz, & Teh, 2000; Tan, Aziz, Teh, & Lee, 2001). In addition, there was some very early work on anthropometry and strength in ten pin bowling (Greenlee, 1960; Sabol, 1963; Widule, 1967) but due to changes in the way bowling is played now and the technological advancement in equipment and lane construction as well as motion capture capability over the past 20 years, care must be taken when interpreting their results. The only research done thus far in the area of bowling technique and biomechanics has been the work commissioned by the FIQ (Johnson, 2002) and the exploratory work of Chu, Zhang, and Mau (2002).

Due to the evident lack of literature in bowling techniques, deriving research questions from previous research results was a tall order. Nonetheless, from the literature in other sports, it is clear that there is a tremendous potential for investigations in the sport of ten pin bowling.

Given the minimal state of available literature, this thesis chose to have an exploratory nature and formed its basis from the following ideas:

Firstly, it is universally understood that in many different types of sports, body dimensions and strength have a significant role. Taller players in basketball and volleyball have an automatic advantage in the respective sports. The stronger athlete will throw further in events such as the shot put and hammer. Indeed, these straightforward examples may not apply to bowling, but it is highly unlikely that body dimensions and strength variables have no relation at all to bowling performance. Thus, recognising if body dimensions or strength variables (or both) are of importance in ten pin bowling, is critical. More specifically, there is a need to identify if there are differences between bowlers of different levels, and between bowlers and non-bowlers. These differences (if they exist), is important for identifying potential bowlers.

Secondly, quantifying bowling performance is rather straightforward, as one would just need to keep and compare the scores. The logical assumption is that bowlers with a better delivery will get the higher score. But this does not provide the whole picture as the delivery itself is a complex sequence of events that can be further broken down into smaller distinct phases. It involves a multitude of variables such as arm swing velocity, and trunk and wrist position in space, therefore it is of great interest to look at how these variables relate to factors such as the ball release speed, and ultimately, to the average score.

Finally, in order to be successful in a competitive environment, bowlers not only need to be able to knock down many pins, they must be able to do it under huge amounts of pressure with changing environment and playing surface conditions. Above all else, to be an exceptional bowler, they have to perform the above mentioned tasks well in many frames of games, in many tournaments, over a period of many months and years, while remaining extremely consistent. Accordingly, the movement variability aspect in relation to playing level is also investigated.

1.3 Objective

The purpose of this study was to determine the critical parameters in ten pin bowling delivery that is important for a good bowling performance. More specifically, this exploratory study was designed to differentiate bowlers by attempting to:

- identify anthropometric and strength attributes that are specific to certain bowlers
- identify kinematic variables that differ between different level bowlers
- identify variability of movement patterns that exists between different level bowlers

1.4 Organisation of the Thesis

A comprehensive literature review about the discussed parameters is provided in Chapter two. It commences with the examination of the effect and relationship of anthropometry and strength characteristics to performance and is followed by an analysis about the kinematics of throwing. A discussion about movement variability in relation to sports performance is also provided. The literature review chapter concludes with a review of statistical methods used in determining critical parameters of sports performance.

Following the literature review chapter, the methodology section is presented in Chapter three. It details the meticulous work involved in the preparation of the motion analysis equipment, which was mostly assembled from scratch under limited budget conditions.

Subsequently, in Chapter four, the results of the studies that form the basis of this thesis are presented followed by a relevant in-depth discussion. Finally, a summary of findings are provided in Chapter five. Practical application and recommendations for future research are also presented in this final chapter**.**

1.5 Significance of Research

The sport of bowling deserves much more attention within the academic research circles as it is a competitive sport that has been accepted into multi-sport games and is played by millions across the globe, either competitively or otherwise.

Being competitive necessitates the need to stay ahead of others. Coaches perpetually strive to find means and ways to adjust and modify a bowlers' technique so that their athletes have the slight edge over other competitors. A study that highlights the technique patterns of a good delivery and identifies the major contributors of a good performance should prove to be invaluable to coaches. Knowledge gathered here will help coaches and athletes alike in restructuring the way training is organised especially in relation to younger players, where motor skill is at the developmental stages (Haywood & Getchell, 2009). It can help change the way bowling is taught and possibly modify certain aspects of the techniques involved, as well as increase the understanding of the common bowling pattern.

The study will also highlight the role of consistency in bowling performance. Coaches and bowlers will have a deeper understanding of its importance in bowling delivery, and knowledge about the areas of the delivery technique that show significant variability differences between good and average bowlers.

Furthermore, by recognising the patterns of delivery and body dimensions most related to good bowling performance, coaches will be able to have a more definitive criterion in selecting potential talents. It has been shown that, even on its own, anthropometrical parameters have a decent relationship to sporting performance (Norton & Olds, 2006), although it is acknowledged that the relationships are not necessarily causal. It is the same for motion analysis, with a number of studies finding links between kinematic and kinetic variables to sports performance (Lees, 2002). A multi-dimensional study that takes into account physical body dimensions as well as movement analysis will be able to provide copious amount of information to identify potential talents.

Finally, with the establishment of normative kinematic, anthropometric and strength data, future research will be able to have a reference point.

1.6 <u>Research Scope</u>

There are numerous factors that influence bowling performance in ten pin bowling. The scope and variables measured for this study was determined in part from the feedback of the state and national coaches (see Appendix 1).The bowling process can essentially be divided into two parts: the 'delivery' in which the bowler has full control of the ball and the 'post release' in which the bowler has absolutely no control over. The interaction between lane condition and ball is a good example of a 'post release' factor that can have a huge impact on score performance (Benson, 2000). This study concentrates *only* on the delivery part of the bowling process. A majority of the components in the delivery is within the athlete's control, hence why bowling is commonly referred to as a closed skill sport (Schmidt & Wrisberg, 2008).

Naturally, all bowlers would want to achieve strikes in all their first ball throws. For this to materialise, firstly, there must be plenty of pin-to-pin and ball-to-pin interaction. For greater interaction, ball momentum plays a significant role. This has resulted in the modern game tactics, commonly being referred to as the 'power game', in which more and more bowlers are using heavy balls and releasing with greater velocity (Benson, 2000). The source and technique in the so called power aspect of the game is of great interest in this study. Secondly, the initiating point (first ball-to-pin contact) has to be *precise* and *repeatable* (at the pocket between the 1st and 3rd pin) so that a more predictable pin-to-pin reaction occurs. In terms of precision, the ball has to follow a curved path so as to be able to reach the targeted pocket. To get to the curved path, the ball has to be spun about its own axis when released from the hand. The aspect of ball spin and the process of generating spin to induce hook is *not* covered in this particular research.

Meanwhile the aspect of repeatability (which is a function of movement variability) has been widely looked into in many sports (Bartlett, 2008) and bowling being a closed skill sport, should have interesting relationships to movement consistency. Therefore, the consistency during the delivery and release is a major point of the study.

The objective of the bowler then, is to manipulate the components of the delivery so as to deliver the ball in such a way that it is able to achieve both the above goals. As with most sports skills, the delivery factors affecting bowler's capability to produce strikes could be also generally categorised as biomechanical, physiological and psychological in nature. The biomechanical factors can be reduced to a deterministic model as advocated by Hay and Reid (1982).

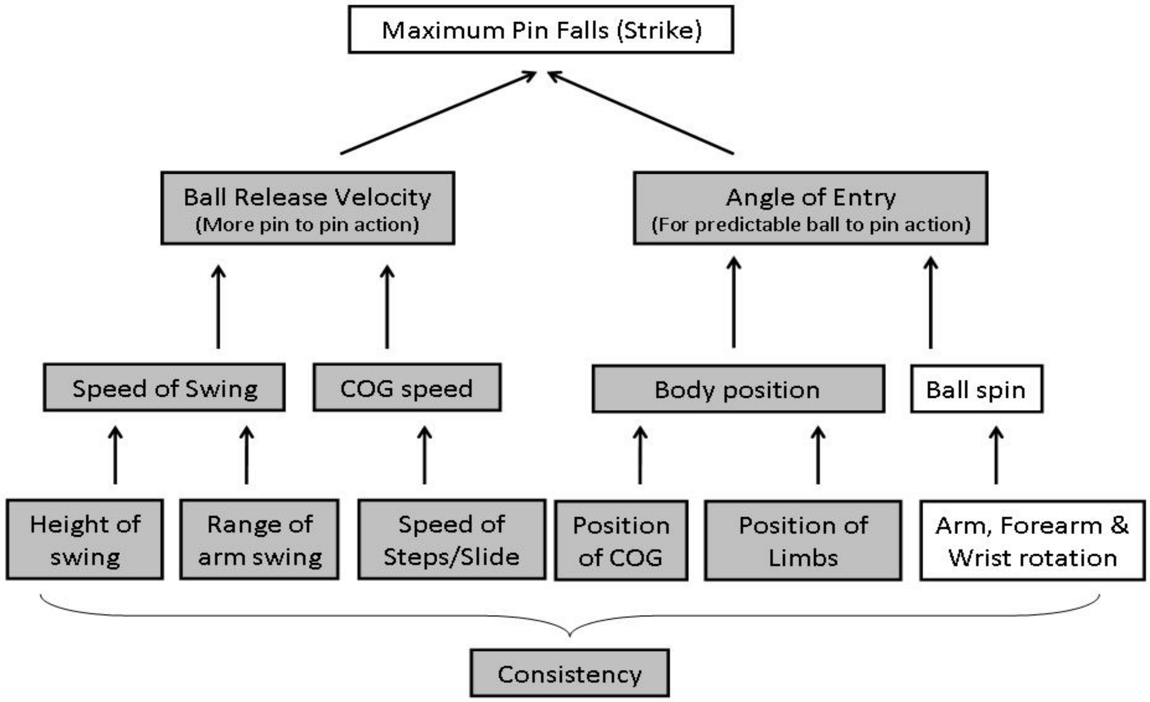


Figure 1.4: Possible biomechanical factors of the delivery in bowling

The diagram in Figure 1.4 can be expanded further because there can be a number of causal variables related to each factor. Nonetheless, this diagram does give a better understanding of the scope of this study. The areas highlighted in grey are the point of interest that were analysed. As discussed earlier, one of the major areas of the study is variability in performing the delivery. The kinematic characteristics of the variables of interest partly determine the number of pin falls, but a single delivery does not win tournaments. Tournaments are won with *consistent* performance. Therefore variability between elite and semi-elite bowlers of the highlighted areas above was compared.

The kinematic and movement variability factors' ability to function in turn depends largely on certain physiological considerations. It has been argued that ten pin bowling is not particularly demanding on the aerobic or the anaerobic systems of the human body

(Rypcinski, 2000). Even though earlier research hardly found relationships between physiological or body dimensions to bowling performance, Tan et al., (2001) still suggested further investigations in this area, as common sense and logic still pointed towards possible connections. For example, swinging a 7 kg ball needs strength and doing it repeatedly will most definitely need muscle endurance. Therefore, the study also looked at how anthropometric and strength attributes could distinguish playing level. Diagram in Figure 1.4 can then be expanded (see Figure 1.5).

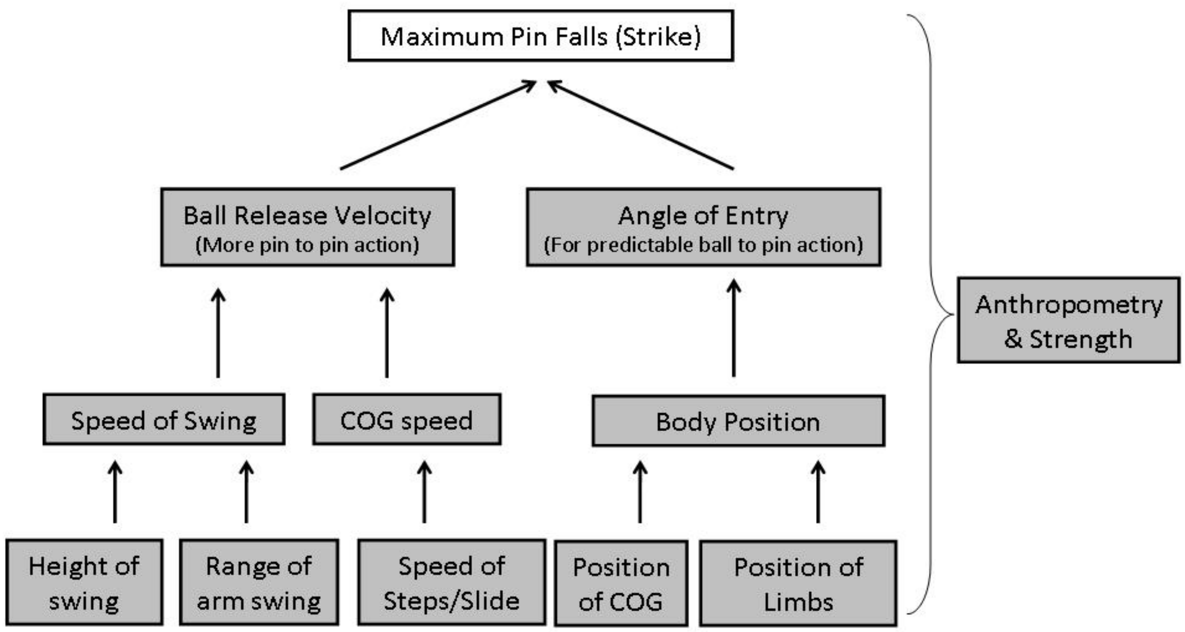


Figure 1.5: Anthropometric and strength possible performance influence

The delivery sequence in ten pin bowling involves many phases, and for each phase there could be a large variation between bowlers, for example, some might prefer a 4-step approach while most would use the 5-step approach. The analysis of critical parameters discussed earlier for this study is focused only on the last step, the slide and the final position. While in terms of the arm swing, the phases of interest will only be from the top of the back swing through to the ball release as illustrated in the highlighted area of Figure 1.6.

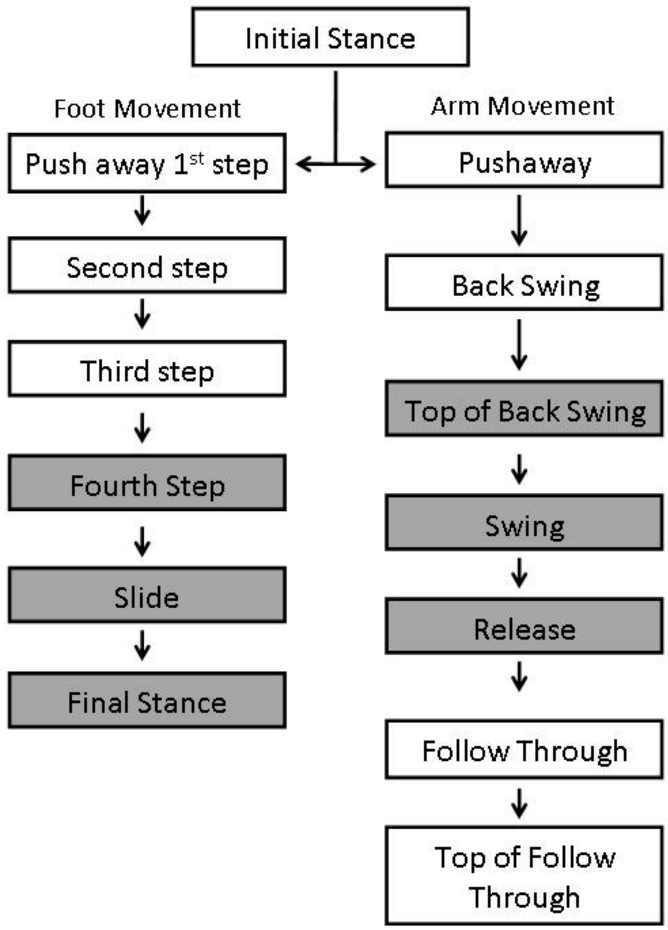


Figure 1.6: Phases of interest of the delivery in bowling

1.7 Delimitations

In terms of technique analysis, this study is delimited to just the final phases of the delivery action. It does not include any actions post ball release. It also only incorporates the first ball deliveries, the outcome therefore should not be generalised for delivery of spares. Rotations along the long axis of the arms and the corresponding ball spinning action were not measured – conclusions would have to bear the lack of ball spin effect on precision. The bowling population is delimited to bowlers in Malaysia with an average bowling score of between 170 to 215 pin falls per game with video recording done under controlled non-competition based environment.

1.8 Limitations

The major assumption of this study is that the bowlers with higher average scores (averaged over the closest three tournaments to the data collection dates) have better delivery techniques. The term 'better' constitutes technique and consistency. Considering the low number of trials as compared to a fully fledged tournament, it is also assumed that the lane conditions prior to the foul line stayed the same throughout the testing period. In terms of measures, the static (isometric) strength test was used instead of one repetition maximum (1RM) dynamic strength tests as the participants were in the competitive season. Due to logistical constrains anthropometric measures were limited to skeletal length and do not include measurement of circumference and skinfold. Finally, common with most motion analysis research, the presence of emotional and psychological factors arising from the knowledge that the movement will be recorded on video and the use of body suit and markers cannot be overcome completely.

1.9 Definition of Terms

Entry Angle: The angle the ball takes when going into the 1-3 pocket (or 1-2).

Approach: Part of the lane from the back of the ball return area to the foul line.

Arm swing: The arc of the bowling arm during delivery.

Bowling shoe: Special shoes for bowlers have a sticky, rubbery sole on the non-sliding foot and harder sole on the other foot to allow slide.

Carry: Ability of the ball to knock down the pins (as in "carry more pins").

Delivery: Includes the preparation up to ball release.

Foul: Touching or going beyond the foul line at delivery.

Foul line: The mark that determines the beginning of the actual bowling lane.

Gutter: Depression approximately 9.5 inches wide to the right and the left of the lane to guide the ball to the pit should it leave the playing surface.

Lane: Playing surface. Wooden or urethane deck pins placed 60 feet from the foul line. Gutters are not part of the lane (see Figure 1.6)

Perfect game: Twelve strikes in a row resulting in a perfect score of 300.

Pocket: The 1-3 pin for right-handers and 1-2 for left handers.

Spare: All pins knocked down with two deliveries.

Strike: All ten pins knocked down on the first delivery.

TBS: Top of Backswing – the maximum point of the backward swing; prior to the start of the forward arm swing

FFS: Front Foot Strike – the point at which the leading foot first makes contact to the lane; prior to the foot slide.

REL: Release – the point of which the ball separates from the bowlers hand.

TOF: Top of Follow-through – the maximum point of the arm swing after releasing the ball.

CHAPTER TWO:
REVIEW OF LITERATURE

Chapter 2: Review of Literature

It has to be noted here, that studies specifically about ten pin bowling are extremely limited. As such, the following review includes literature that mostly revolves around other throwing related events or events with a throwing-like motion.

2.1 Anthropometry and Strength - its Relationship to Performance

Optimal performance in sports is the result of an intricate blend of anthropometric, physiological, biomechanical and psychological factors. Scientific procedures are useful to identify those attributes, and the level of contribution of those attributes that are essential for successful performance. Once identified, these attributes may also be used for talent identification and to develop more specific assessments. Furthermore, it may assist the coach or sport scientist to construct a training program that develops all of the essential attributes to the levels required for success.

Interest in anthropometric characteristics and physical characteristics of sportsmen from different competitive sports has increased tremendously over the past few years. It has been established that specific physical characteristics or anthropometric profiles indicate whether the player would be suitable for the competition at the highest level in a specific sport (Claessens, Lefevre, Beunen, & Malina, 1999; Reilly, Bangsbo, & Franks, 2000)

The relationship between body build and general physical performance has been investigated in-depth by many researches over the past years, with most indicating significant relationships between certain anthropometric parameters and general physical performance (Ross & Marfell-Jones, 1991). To exemplify this, Fuster, Jerez, and Ortega

(1998), in a study with 303 participants found that vertical jump performance was related to length of a number of body segments of females and males, while body mass was correlated with performance in static strength tests. Subsequently, Visnapuu and Jurimae (2007) examined basketball and handball players and found that measured finger length and hand perimeters correlated significantly to hand grip strength.

On the other hand, there are a minority who do not support the notion that relationships exists between body build and physical performance. For example, in a study involving recreational athletes who were tested on vertical jump performance, Davis et al., (2006) concluded that although there were minor relationships between segment length and vertical jump performance, skeletal length measurements were opinioned as having no predictive value on performance. However, the consensus though, appears that anthropometric dimensions and morphological characteristics play an important role in determining the success of an athlete (Wilmore & Costill, 1999; Keogh, 1999).

The possible causal link between physical characteristics and specific sports performance is not as straightforward as there is an array of various different types of sports, and within each sport there are a multitude of performance variables. The research resources are spread thin with some sports such as soccer, athletics, aquatics/water sports, American football and volleyball having established relationships, while other sports such as ten pin bowling, there are practically not even any known anthropometric database to speak of.

Over the years a number of studies on anthropometric and strength characteristics have successfully managed to discriminate between good and average athletes in a range of diverse sports including rugby union (Rigg & Reilly, 1988), rugby league (Gabbett, 2002), soccer (Hoare & Warr, 2000), and Australian football (Keogh, 1999). Thissen-Milder and Mayhew (1991) demonstrated that selected physiological and anthropometric characteristics could successfully discriminate among freshman, junior varsity, and varsity volleyball players, and between starting and non-starting players. In a more recent study, Gabbett and Georgieff (2007) reported significant differences among junior national, state, and novice volleyball players for stature, standing reach stature, skinfold thickness and vertical jump. In addition, Fry and Kraemer (1991) concluded that power clean, bench press and vertical jump height were good discriminators between division of play and playing ability in American football players.

In relation to aquatic sports, water polo studies have shown that the diameter of the femur and the biacromial were correlated positively and significantly with goal shooting velocity (Vila, Ferragut, Argudo, Abraldes, Rodriguez, & Alacid, 2009; Van der Wende, 2005). Furthermore, Feltner and Taylor (1997) discovered that chest, upper body, and forearm circumference measures may be causal determinant in the choice of technique style in throwing the ball. More interestingly, Tan, Polglaze, Dawson, and Cox (2009) found that they were able to statistically discriminate water polo player position within a particular team by analysing the anthropometric and strength data alone.

A throwing sport that has garnered a lot of spectator as well as research interest because of its explosive exciting nature is cricket fast bowling. Mechanically, it is known that a longer radius is advantageous in generating higher rotational velocity, and this has been shown to be true in cricket whereby longer arm segments was significantly related to higher ball velocities (Glazier, Paradisis, & Cooper, 2000). Correspondingly, chest girth was also related to higher ball velocities (Portus, Sinclair, Burke, Moore, & Farhart, 2000) whereby other than being an indication of bigger upper body muscles, chest girth could also alter the pivot point of the upper body rotating parameter. Apparently the relationship is very much dependent on the playing level – only senior bowlers with more established techniques had their ball velocities affected by arm length (Pyne, Duthie, Saunders, Petersen, & Portus, 2006). The latter example possibly points out that segment length, although theoretically should have an effect of performance, seem only significant once the athletes movement patterns are well developed.

In another predominantly overhand throwing sport, Marques, Van den Tillaar, Vescovi, and Gonzales-Badillo (2007) looked at strength variables in relation to handball throwing performance and found that absolute bench press strength was correlated to ball velocity. Even for static strength, Van den Tillaar and Ettema (2004b) demonstrated that isometric strength positively related to higher throwing velocity in experienced male and female handball players.

Meanwhile, for underarm throwing pattern, the movements which are most similar to ten pin bowling would be the windmill softball pitch and the release in lawn bowl. Neither of the two had any known available data on physical body parameters in relation to performance. Alternatively, looking at underarm type motion in golf, Keogh, Marnewick, Maulder, Nortje, Hume, and Bradshaw (2009) reported that better golfers were stronger in golf specific strength compared to lower level golfers and that higher golf-specific strength test scores were also correlated significantly to higher club head velocities. This relationship is evident too in baseball batting whereby a strong correlation between muscle strength and hitting success existed (Gebhardt, Bowers, & Archer, 1991).

The discussions above had led to the belief that there was a decent link between physical characteristics and specific sports performance. Consequently, it is safe to assume that it is also therefore possible to utilise this knowledge for identifying new talents. The assessment of the physical characteristics of successful competitors can provide further information regarding the prerequisites of sporting success. The measurement of body dimensions can provide an appraisal of the structural status of an athlete and therefore may be used to describe the 'typical' athlete that succeeds within a certain sport (Ross & Marfell-Jones, 1991). A range of relevant anthropometric and physiological factors can be considered in talent scouting which are subject to strong genetic influences (e.g. stature) or are largely environmentally determined and susceptible to training effects (Reilly et al., 2000).

Based on comparison between youth athletes and their peers, Zhang, Chen, Zhang, Li, and Zhou (2009) recommended that the typical anthropometric indices that should be considered in recruitment for women volleyball players include body mass, stature, sitting height, subscapular skinfold, ankle girth, forearm girth, biacromial breadth, and Achilles' tendon length. In elite youth handball, players were heavier and had greater muscle circumferences than their non-athletic peers (Mohamed et al, 2009), while Reilly, Bangsbo, and Franks (2000) concluded that anthropometric and physiological criteria do have a role as part of a holistic monitoring of talented young soccer players. This was corroborated by Wong, Chamari, Dellal, and Wisloff (2009) by providing a scientific rationale behind the coaches' practice of selecting young soccer players according to their anthropometry for short-term benefits, such as heavier players for higher ball shooting speed and 30 m sprint ability. However the authors also noted that such a practice was not justified in the long-term process of player development as although the distinctions are evident in adult and elite youth players, their existence must be interpreted carefully in talent identification and development programs.

Moving on specifically to bowling, over the years the sport has attracted various types of participants, both large and small. It is argued to be a sport for all (Cheah, 2009; Wiedman, 2006) and has also been labeled a gender neutral sport (Thomas, Schlinker, & Over, 1996), as it involves a seemingly low reliance on absolute strength, power and fitness (Tan et al.,, 2000). Consequently, it is relatively common to have women's scores equaling or even exceeding the men's.

Currently, it is estimated that there are approximately 100 million bowlers worldwide, with about 10 million participating competitively (FIQ, 2010). Yet, research in ten pin bowling is surprisingly scarce (Tan et al., 2000). Even more lacking are studies related to physical and physiological parameters, with a handful of older unpublished theses (Curtis, 1951; Greenlee, 1960; Sabol, 1963; Widule, 1967)] and only two recently published work (Tan et al., 2000; Tan et al., 2001). These studies are in a disagreement over the relationship between strength and anthropometric variables with bowling performance. Some studies had found significant relationships (Curtis, 1951; Sabol, 1963), while others had not (Greenlee, 1960; Widule, 1967and Tan et al., 2001).

In two of only a few available published works on bowling, Tan and colleagues (2000; 2001) concluded that bowlers of relatively diverse age and build can be equally competitive in the sport of ten pin bowling. The authors did not find any strong relationship between grip strength, lower body strength and flexibility to bowling performance, and summarised that on the whole, the common physiological measurements do not adequately predict performance in the sport of ten pin bowling at the elite level. The authors went further to suggest that other factors such as mental skills and technique were more likely to have a greater contribution to bowling success. Although no significant relationships was established, it was suggested that there might be a threshold for strength with regards to bowling successfully, after which further strength gains do not necessitate better performance.

Considering the small number of empirical research conducted to date, there is a need to further explore the influence of strength and anthropometric variables on bowling performance and identify how bowlers of different playing abilities differ in terms of these variables. There is also no known study that has tried to discriminate bowlers of different playing abilities by utilising anthropometric and strength attributes.

The choice of physical characteristics tests and measurements used in previous studies was varied. Measurement of anthropometric and body dimensions were widely used, with measurements such as height, weight, segment length and breadth taken in many studies (e.g. Barker et al, 1993; Barett & Manning, 2004; Gabbett & Georgieff, 2007, Reilly et al., 2000; Thissen-Milder & Mayhew,1991) but the choice of strength tests was not so obvious. Strength is one of the more commonly conducted tests in sports and has been used to discriminate different level athletes (Barker et al., 1993) as well as to track training progress. Although dynamic sports specific maximal strength test (e.g. 1RM) would be the ideal strength gauge, its use for in-competition bowlers as the case in this current study, was risky. Alternately, isometric strength tests have been shown to have high correlations with dynamic strength tests (Baker, Wilson, & Carlyon, 1994; McGuigan & Winchester, 2008) as well as showing correlations with real-world throwing performance (Van den Tillaar &

Ettema, 2004b). The use of isometric tests has come into question only when looking at training adaptations in experimental conditions over a period of dynamic movement training (Baker, Wilson & Carlyon, 1994), but its use in cross-sectional, group-comparison type studies seem to be acceptable.

Among the variables measured in Tan and colleagues (2000) study on the relationship between bowling performance to physiological and physical characteristics of bowlers included height, weight, grip strength and lower body strength. Due the limited literature in ten pin bowling, the final choice of test battery used in this current study was made after discussions with the national team coaches (Cheah, 2009) pertaining to the available tests and measurements that were possibly related to bowling performance.

2.2 Kinematic Analysis of Throwing

Throwing is a one of the many natural movement patterns in humans. Just as walking and jumping, it is a basic motor function that is used for daily living. A person's throwing pattern is acquired through the normal motor development process, which tends to happen at the early ages of human growth (Marques-Bruna & Grimshaw, 1997). Throws can be subdivided mechanically into three distinct phases - preparation, action, and recovery, with the base of support in the direction of the force being applied. The patterns can also be generalised into three groups, that is, the side arm, overarm and underarm. Throws are done in either one of these styles or possibly a combination of two. Atwater (1979) was the first to distinguish between the overarm and sidearm throwing patterns in terms of the direction in which the trunk is laterally flexed. When lateral flexion occurred away from the throwing arm, and overarm pattern was used, while lateral flexion toward the throwing arm indicated a sidearm pattern. The underarm pattern is distinguished by motion predominantly in the sagittal plane. Broer (1969) was the first to highlight the similarity of these movement patterns used in seemingly dissimilar activities such as the overarm pattern seen in the fast bowl in cricket, the badminton smash, and the volleyball spike.

It is possible to distinguish throwing-like motions for distance, in which segments rotate sequentially, and pushing-like motions for accuracy, in which segmental rotations occur more simultaneously. Sequential movement of the body segments results in the production of a summated velocity at the end of the chain of segments used. Sequential segmental motions are most frequently used to produce fast velocities in external objects. Depending on the objective of the skill (i.e. speed for distance, accuracy, or a combination), modifications in the sequential pattern may be involved, larger or smaller ranges of motion might be used, and longer or shorter lever lengths may be chosen. However, few throws in sport have no accuracy requirements. In some throws, the objective is not to achieve maximal distance but rather accuracy or minimal time in the air (such as throwing back to the wicketkeeper in cricket). In such throws, the release speed, height and angle need to be such that the flight time is minimised within the accuracy and distance constraints of the throw (Bartlett, 2008). In accuracy-dominated events, such as dart throwing, the athlete needs to achieve accuracy within the distance constraints of the skill. The interaction of speed and accuracy in these skills is often expressed as the speed-accuracy trade-off (Bartlett, 2008).

Ten pin bowling falls under the underarm throwing pattern but the objective of the ‘throw’ is rather unique. Unlike darts, ten pin bowling is not predominantly accuracy orientated. In modern bowling, the emphasis is on the power game (Weidman, 2006). On one hand, bowlers need to target the pocket of pins 1 and 3 (right handed bowlers) but at the same time the ball needs to have enough momentum to knock down the rest of the pins through pin-to-pin interaction (carry). To have high momentum, the ball mass in ten pin bowling is higher than any other ball sports. Compounding matters, to have any chance of hitting the specified pocket, the ball needs to be excessively spun to produce a hooked trajectory, as a straight ball will need to be delivered from the next corresponding lane to have chance at hitting the target. These unique demands make ten pin bowling unlike any other throwing sports.

2.2.1 Segment Contribution and Sequentiality

Early work in the analysis of segment contribution was done primarily with joint immobilisation (Miller, 1980). Although the methods are crude and has near zero ecological validity, it did provide the base understanding of how humans perform throwing motor tasks. The typical finding was that the distal segments had higher speeds than proximal ones (Atwater, 1979). With the advancement of motion analysis technology, segment contribution analysis in sporting movements has been more precise with higher ecological validity.

Quantifications of segments' landmark linear velocities in primarily speed objective overarm and sidearm throws have demonstrated a characteristic sequence pattern of proximal to distal increases in segment velocities in water polo penalty throws (Elliott & Armour, 1988), javelin throws (Whiting, Gregor, & Halushka, 1991), baseball pitches (Elliott, Grove, Gibson, & Thurston, 1986), tennis serves (Elliott, Marsh, & Blanksby 1986), tennis forehand drives (Elliott, Marsh, & Overheu, 1989) and basketball free throw (Hayes, 1988). It seems that the segment contribution pattern and proximal-to-distal sequence are present for both genders of the same skill level, as demonstrated by Mero, Komi, Korjus, Navarro, and Gregor (1994) in their work with javelin athletes.

By looking at segment contribution, researchers have made many conclusive statements that have contributed immensely to the knowledge base of the particular sport in terms of performance enhancement, training specificity and injury risk management. For example, it is now known that in baseball (and most other overarm throwing patterns), the biggest contributors towards ball velocity are elbow extension and internal rotation of the shoulder (Van den Tillaar & Ettema, 2004a). Studies in tennis also concurred, that a majority of the racket head velocity in the tennis serve is attributed to internal rotation, elbow extension as well as wrist flexion (Gordon & Dapena, 2006).

More interestingly, in softball windmill pitching (an underarm pattern much like in ten pin bowling) there is also evidence of proximal-to-distal sequence. Alexander and Haddow (1982) concluded that there was a definite proximal-to-distal sequence of the softball pitching motion, with decelerations occurring in the proximal segments prior to release of the ball. Oliver, Dwelly and Kwon (2010) agreed that there was evidence of sequentiality among the arm segments, but only in the intermediate and advanced softball pitchers. In terms of segment contribution, the novice athletes tended to rely more on the upper arm and forearm. The authors summed that emphasis should not be placed on the shoulder alone, but training and conditioning methods should focus on the entire kinetic chain including the torso and the full arm segment in an attempt to attain the highest velocity in the windmill softball pitch.

2.2.2 <u>Kinematic Differences in Technique</u>

Since the the introduction of the direct linear transformation (DLT) method by Abdel-Aziz and Karara (1971) and the inception of video technology which replaced the cumbersome film, 3D motion analysis has developed by leaps and bound. Comprehensive kinematic description of the baseball pitching motion, for example, was done using 3D motion analysis as early on as 1986 by Feltner and Dapena. Further research extending from the kinematic descriptive studies were on segment contribution of various sports skills, which are since not uncommon. Kinematic analysis and joint contribution has been investigated in a range of diverse fields including cricket (Portus et al., 2000; Glazier, Paradisis, & Cooper, 2000), javelin (Mero et al., 1994), tennis (Gordon & Dapena, 2006; Elliott et al., 1989) and baseball (Matsuo, Escamilla, Fleisig, Barrentine, & Andrews, 2001; Fleisig, Barrentine, Zheng, Escamilla, & Andrews, 1999).

From the earlier work of kinematic description of sports technique, biomechanists have more recently looked at identifying the best techniques for specific motor tasks. The 'ideal' performance is derived by comparing elite to the non-elite athletes or through statistical prediction such as multiple regression analyses or through computer aided modeling. In relation to this, there are also a number of studies that compared differences between men and women's technique.

The sport that has received one of the widest coverage is the throwing events in athletics. The early 2D work of Gregor, Whiting, and McCoy (1985) in discus, suggested that there were little difference between men and women regarding the angle and velocity of release but larger differences were observed in foot position at release and height of release between men and women. Years later, more in depth 3D analysis by Leigh and Yu (2007) concluded that the relationships between technical parameters and discus throwing performance are generally different for males and females. Their results suggest that elite female discus throwers are reliant on effective technique to achieve long distances, whereas male discus throwers have a relatively homogeneous technique, and a dependence on physical strength to achieve their long throws.

Similarly, Alexander, Lindner, and Whalen (1996) found gender differences for technique parameters in shot put. The authors reported quantifiable predictors of performance in both males and females and that the predictors were differentiated by the sex of the athlete. For the male throwers, centre of mass speed during glide, vertical acceleration of centre of mass during delivery, and trunk angle at the start of glide were the most important parameters to produce longer throws. On the other hand, the critical parameters for female throwers included knee extension during the glide, elbow speed during delivery, and a greater shoulder flexion angle at release. Another study on elite female shot putters highlighted other critical parameters for success, that is, knee flexion angle at both rear foot touchdown and release along with a neutral shoulder-hip angle at release (Young & Li, 2002).

Gender differences were also observed in javelin, whereby LeBlanc and Mooney (2004) stated that men and women had significantly different trunk and implement angles at various points during run up to release. The difference in trunk and consequently javelin angles were said to possibly contribute to the huge disparity of around 70% difference between the distances thrown. Looking at male athletes of different levels, Bartlett, Stockill, Elliot, and Burnett (1996) did not find differences in javelin angles but instead concluded that better performance was dependent mostly on release speed. Release speed in turn was dependent on peak velocities of the body and upper limb segments as well as timing sequence of the lower limbs. Relationships between segment peak velocity and performance was also found in shot put (Alexander et al., 1996). The reliance on velocity (and hence, strength and power) was in agreement with Whiting et al., (1991) as well as Leigh and Bing Yu's (2007) work on discus and Young and Li's (2002) work on shot put.

All three field events discussed above are speed outcome oriented, as the objective was to get maximal distance, hence the logical positive relationship between performances and segment velocities. There were a number of discrete variables at specified phases that were good predictors of performance. In general, it can be agreed that there were significant differences between genders in the techniques used to achieve the same speed outcome goals.

In a landmark study involving youth, high school, college, and professional baseball pitchers performing a speed and accuracy outcome movement (pitching), Fleisig and colleagues (1999) found that only one out of the 11 discrete position parameters had shown significant differences between groups, but all five velocity parameters had shown significant differences. None of their six temporal parameters showed any significant differences between the groups. Adding to this, a more recent study found that two temporal parameters and three kinematic position parameters were significantly related to increased ball pitching velocity (Stodden, Fleisig, McLean, & Andrews, 2005). Considering that the variables recorded in both studies were not similar (which cumulates to 11 different kinematic variables), it generates an assumption that temporal, velocity and position kinematic data could possibly differentiate different level performers.

Although a close relative to the sport of baseball, totally dissimilar findings were reported for pitching in softball. It is one of the very few ball throwing sports that utilises the underarm pattern motion – the others being lawn bowls and ten pin bowling. Alexander and

Haddow (1982) had looked at four highly-skilled pitchers from the sagittal aspect only, with the resulting kinematic analysis indicating that one of the critical parameters was the ability to decelerate segments, which likely require very strong eccentric contractions of antagonistic muscle groups. Surprisingly for a former Olympic sport, there were no other known studies that looked at relationships between kinematic variables to pitching performance as majority of work published had mostly revolved around possible injury risks in relation to pitching technique (Werner, Jones, Guido, & Brunet, 2006).

Meanwhile, delivering the ball in cricket is a different ball game altogether – it is more an overarm technique as compared to sidearm in baseball and underarm in softball and it allows for a run-up preceding the release. There are two different ways to hit the wicket (target), either by ‘tricking’ the batsman by excessively spinning the ball (accuracy outcome objective) or to try move the ball faster than the batsman can react (accuracy and speed outcome objective); or a combination of both. Consequently, at the extreme ends of the continuum, there are the spinners and the fast bowlers. Due to vast number of types, variations and variables involved in spin bowling, the majority of technique analysis in cricket has been centered around fast bowlers. In one study, Salter, Sinclair, and Portus (2007) using a multiple stepwise regression analysis, showed that 87.5% of the within bowler (single bowler) variation in ball release speed can be attributed to run-up velocity, angular velocity of the bowling arm, vertical velocity of the non-bowling arm, and stride length. Another study had found that increased shoulder counter rotation movement was related to better bowling accuracy (Portus et al., 2000). From these studies, it appeared that both accuracy and speed outcomes objectives can possibly be predicted from kinematic data.

Prior discussions had centered on activities that have a primarily speed outcome objective with a defined accuracy constraint. Alternatively, in rugby line-out throw (a movement that has a speed-accuracy trade-off), Trewartha, Casanova, and Wilson (2008) found that players exhibited greater accuracy at shorter throwing distances, although the accuracy decrement was less in the elite. Participants demonstrated different alterations in technique when performing throws of longer distances, either showing increased magnitudes of upper-body joint angle velocities (less accurate thrower) or lower body joint velocities (more accurate thrower). Meanwhile, Miller and Bartlett (1996) had examined basketball shooting from different distances and found that there were increases in release speed as shooting distance increased, which was explained by increased angular velocities of both shoulder flexion and elbow extension and an increased speed of the centre of mass in the direction of the basket. Players also exhibited an earlier timing of release as shooting distance increased.

To summarise the discussions about technique analysis and performance, it is clear that better performance can be predicted from kinematic data. For primarily speed outcome objective, release speed and segment peak velocities seem important. For sports where speed outcome is required within an accuracy constraint, a number of discrete spatial data appear to be predictive. As for movements with a speed-accuracy trade-off requirement, a combination of segment velocities and temporal data were of importance. Also, it seems that men and women utilise different techniques to achieve same performance goals.

Moving on to the sport of ten pin bowling, surprisingly, research and literature on the biomechanical aspects of bowling are extremely scarce for a sport that is popular in most parts of the world. Being a closed motor skill, most studies have been directed towards the psychological and mental aspects of performance. There are also various works on bowling balls and bowling lane preparation, but hardly any known studies on the bowling techniques. Therefore coaches and athletes are devoid of any methodological skill analysis and knowledge.

To date, one study that tried to describe the kinematics of bowling delivery was done by Johnson (2002) and the findings are only available on the FIQ website. In that study, it was concluded that a novice player took fewer steps to deliver the ball, produced a slower, less controlled ball at release as compared to elite bowlers. The novices also tended to have an erect body posture at release with an extended leading leg and very restricted shoulder movement. In addition, the beginners usually released the ball at a higher vertical height, thus letting the ball bounce. Elite players were able to get a curvilinear ball path resulting in less dependency on ball speed. Extreme care must be noted when interpreting this work as it utilised unclear methodology and were discussed mostly qualitatively without any concrete statistical comparisons. There is also a possibility that some findings may be biased as the research was commissioned by FIQ. To illustrate, a majority of the discussions had advocated bowlers as skilled athletes, thus lending support and leading to the idea that ten pin bowling should be included as a future Olympic sport.

In the other only known technique analysis study done on ten pin bowling, Chu et al., (2002) attempted to profile 12 elite level ten pin bowlers in terms of delivery technique and to compare the male and female bowlers. The study utilised 2D motion capture and was done without joint markers. The authors found that the male bowlers slide foot stopped further away from the foul line compared to the female counterparts. Shoulder angles at release and at top of back swing were also different between genders. Although a rudimentary study, the results indicated that in terms of technique, bowlers like their counterparts in other sports, can also be distinguished by discrete kinematic data. Further research into the areas of performance techniques and segment contribution in ten pin bowling would yield tremendous benefits. Among other things, one would be able to establish which kinematic patterns contribute the most toward a good delivery in bowling, recognise and isolate the sequencing or movement patterns that are synonymous with better bowlers, and dissipate this knowledge to coaches and lower level athletes.

2.3 Within-Subject Movement Variability in Sports

Most early sports-related variability studies analysed only one trial per individual. With the advent of automatic marker tracking, it is now easier to track multiple trials per individual, opening up new opportunities. One of the advantages of collecting multiple trial kinematic data is the ability to gauge within-subject variability, whereas previous works had reported mostly on inter-subject variability. In event where the number of participants is sufficient, comparisons of the within-subject variability between the participants can be made.

Movement consistency has always been understood to have some implications to performance and different motor control paradigms offer different views on variability. There have been earlier arguments from the cognitive motor control perspective that generally, consistent movement patterns leads to better performance (Higgins and Spaeth, 1972). These cognitive motor control theorists traditionally considered variability as undesirable system noise, or error, and saw variability as reducing with skill learning as the learner freezes unwanted degrees of freedom in the kinematic chain (Bartlett, Wheat, & Robins, 2007). Alternately, ecological motor control advocates view variability as having a functional role in human movement whereby variability is seen as essential in giving flexibility to adapt effectively to changes in the environment. More recent studies have indicated that even the best athletes are not able to replicate the exact same movements in achieving good scores (Miller, 2002). There seem to be no such thing as “standardized movement pattern” for the best performance (Bauer & Schollhorn, 1997).

This has led to the belief that outcome consistency is not dependent on movement consistency. In actual fact even for outcome consistency, Woo and Zatsiorsky (2006), in their retrospective study of athletic throwing event performance at major games, found that the performance scores variance was slightly larger in the best athletes and was larger in female athletes than in males in all events. With the improvement of the performance outcome level, the percentage of the successful (not fouling) throwing attempts increased. It was concluded that with higher ranked athletes, the dependability of the athlete’s performance improved, while the performance variability did not change irrespective of the athletes’ level. The study basically summed that elite throwing athletes did not show particularly consistent outcome scores during big events, and as mentioned earlier, even when they did achieve their ‘best’ throws, Bauer and Schollhorn (1997) suggested that they possibly did it with variable motor patterns.

Movement variability in performing sport skills has been studied in various throwing disciplines such as javelin, baseball and basketball. In baseball pitching which has a speed-outcome objective within an accuracy constraint, Stodden and colleagues (2005) investigated the relationship between pitching mechanics and ball velocity within individual athletes, with a total of 166 fastballs thrown by 19 healthy adult pitchers analysed. The authors found that lower variability in three kinematic, three kinetic, and two temporal within-subject parameters correlated with more consistent ball velocities. Furthermore, when comparing different level pitchers, Fleisig and colleagues (2009) found that there was a significant overall difference in kinematics and in six of the eleven discrete kinematic parameters analysed. Individual standard deviations tended to be greatest for youth pitchers, and decreased for higher levels of competition. Thus pitchers who advanced to higher levels exhibited less variability in their motions. Meanwhile, in terms of consistency throughout a game, Escamilla and colleagues (2007) digitised ten college pitchers during a simulated game and reported that kinematic and kinetic variability for a pitcher from start to end of a game was relatively low. Looking at studies on baseball pitching alone has led to the understanding that variability of segment motions was related to consistency of performance; that skilled performers had more consistent patterns, and that movement patterns can be quite consistent throughout a game.

In an example of a solely speed-outcome event, Bartlett (2008) and Bartlett, Muller, Lindinger, Brunner, and Morriss, (1996) reported intra-individual differences in novice, club, and elite javelin throwers, with intra-individual differences greater for the novice and elite throwers than for the club throwers. Generally, this showed that even athletes in events striving for maximum distance do not generate identical coordination patterns.

For movements with a speed-accuracy trade-off, specifically basketball shooting, Robins, Wheat, Irwin, and Bartlett, (2006) reported considerable variability between trials in discrete segment variables from various distances. However, Miller (1998, 2002) found no significant differences in speed variability between successful and unsuccessful shots and this finding was attributed to possible compensatory variability during the final finger-ball contact (which was not measured). Miller’s assumptions were supported by Hayes (1988) who found high ball velocity variability among subjects prior to release but this variability was greatly reduced at release. The low variability in velocity at release was most likely accounted for by the narrow limits of velocity required to drop the ball in the basket from the foul line. Vaughn (1993) also found that generally, movement patterns in shooting was inconsistent and summed that there was no evidence from their study that a free throw shooter can retrieve a motor program from memory and precisely reproduce that movement pattern. This discovery suggested that intra-individual variability is an inherent component.

Interestingly, Miller (2002) too found an increasing trend in absolute variability of joint speed along the sequential segment chain whilst taking the shot, which was corroborated by Robins and colleagues (2006). Thus it was apparent that although the final release ball velocity in shooting appeared consistent, the movement patterns leading up to the release was inconsistent. However, improvements in skill level appear to be associated with an increasing amount of inter trial movement consistency especially from the elbow and wrist joints (Button, Macleod, Sanders, & Coleman, 2003)

Besides spatial variability, some researchers chose to solely look at temporal variability, more so for ball-implement impact tasks. It was demonstrated that expert performers in a number of games (i.e., baseball, table tennis and field hockey) executed their drives with more consistent movement times (Bootsma & Van Wieringen, 1990). It appeared that the time between the first forward motion of the implement and the moment of ball contact varied little between trials. However this consistency was not apparent in throwing where Fleisig and colleagues (2009) reported no differences in temporal variation, concluding that coordination was not improved at higher levels. Furthermore, Matsuo and colleagues (2001) found that the variability of timing among pitchers decreased from early to late parameters in the throwing motion, and argued that timing early in the throw may be the key to ball velocity. Throwing is a process that proceeds from the ground up, and energy is transferred from the larger lower proximal segments to the lighter upper distal segments. The implication was that throwers can, to some extent, adjust in response to early inconsistencies in their movement timing to produce a more consistent end result (Fleisig et al., 2009).

Currently, there are no published studies on movement variability of the delivery in ten pin bowling, but there is one known unpublished thesis that is related to variability, hence it merits some discussion. In that thesis, Harris (2008) in labeling ten pin bowling a "physical tasks with self-paced requirements", used movement variability as a tool to investigate internalised mental representations. It was argued that there were two approaches to motor performance - the expert performance approach, which proposes cognitive mediation of task performance via mental representations versus the ecological/dynamical systems approach, which proposes the environmental information as the primary mediator of performance, the former of which was hypothesised to be applicable to ten pin bowling. To address his research question, Harris used bowling under normal conditions against bowling under obscured conditions as the experimental approach.

Without further discussions into the second part of his study (bowling under obscured conditions), the first part which constituted normal bowling conditions found that skilled participants exhibited low levels of execution variability and high success rates during normal spare and strike conditions. Success rate was negatively correlated with execution variability, i.e., the greater the amount of execution variability exhibited by the participant, the lower the participant's score, on both spare and strike trials. There was also a significant negative correlation between execution variability and skill level on both spare and trials. Thus, low levels of execution variability were associated with higher success rates and higher skill level.

Unfortunately, there were two major concerns with the study. First was the range of subjects used. The averages for the skilled bowlers group ranged from 170 to 240 (mean score = 200.67). The novice group had a bowling average of 120 or less. The averages for the novice bowlers ranged from 50 to 120 (mean score = 103.75). Comparisons between the two distinct groups would be acceptable, but correlation analysis was questionable as there were no bowlers in the mid-range scores. Second was the choice of motion capture and variability calculations methods. The use of 38 mm table tennis balls would introduce higher variance of measurement during digitising as well as higher movement artefacts from the large markers. Reflective markers used in biomechanics are usually only around 15 mm in diameter and made from Styrofoam which is lighter. The methods of measuring variability were also unclear, in addition to the trials being not time-normalised to facilitate between-trials comparisons. In view of these methodological shortcomings, results of Harris's (2008) work in terms of biomechanical interpretation should be viewed with caution.

In summary, movement variability was found in real sports competitions, with strong ecological validity, in simulated field conditions, and in laboratory conditions, with strong research validity (Bartlett et al., 2007). More importantly, varied motor patterns have many potential benefits as highlighted by Bartlett (2008). In the context of this study, the benefits of the ability to vary motor patterns include being able to facilitate changes in coordination as in learning new motor skills, being able to adapt to changes in the environment such as deteriorating lane conditions in ten pin bowling, and being able to modify tissue loads from repeated ball deliveries thereby reducing injury risks. As such, investigation into the critical variability parameters is warranted.

2.4 <u>Statistical Methods for Determining Critical Parameters</u>

From an overall perspective, despite the lack of work examining critical parameters in ten pin bowling, attempting to determine the critical parameters in other sporting events was not something new. The more common statistical method used for identification of critical parameters in previous studies was regression analysis. An example of a study that illustrated the use of regression analysis was by Hay, Vaughan, and Woodworth (1981), whereby the authors had proposed a model for the standing vertical jump by describing the performance parameters in the skill and analysing data from a large number of athletes to evaluate the model. In that study, the correlation of each parameter in the model with the jump height was calculated to determine which parameters might be most important, followed by a multiple regression analysis to determine which of the parameters contributed most to explaining the performance of each individual.

Some of the other sporting techniques that have been analysed in this manner include triple jump, sprints and hurdles, ice skating and shot put (Young & Li Li, 2005). These studies had provided insight into the technical parameters of the events that were most closely related to success, and which parameters were the best predictors of performance. Importantly, the previous analyses of critical parameters in various sports had involved continuous variables as the dependent variable (i.e. distance thrown or jumped, time of race completion), which led to the use of the multiple regression analysis. In this study, the dependent variable was categorical, that is, groups based on playing level. Instead of looking at parameters that contributed most to explaining performance, this study looked at parameters that best distinguished the groups. Hence, the discriminant function analysis was used.

CHAPTER THREE:
RESEARCH METHODOLOGY

Chapter 3: Research Methodology

Research Design

The present study used a non-experimental cross-sectional research design, and is exploratory and descriptive in nature. Participants were grouped based on their playing level and were categorised as elite and semi-elite bowlers. Data collection was carried out for five days. Measurements for each subject were taken in the first half of the day on one of the five days, prior to the commencement of their regular training session.

For the study involving anthropometric and strength measurements, a third group made up of sedentary university students was chosen to allow for comparisons between the bowlers and a representation of the normal population.

Participants

A total of 30 national and state bowlers that were in competition during the current season and had various competitive years of experience were recruited. Subjects were assigned into either elite or semi-elite groups according to their average bowling score over three major tournaments nearest to the data collection date. Subjects with a Bowling Score Average (BS_{ave}) of 200 pin falls and above were placed in the elite group, while the other bowlers were placed in the semi-elite group. There were 10 male elite (Age 23.6 ±3.9; Experience 11.2 ±3.7 years), 8 female elite (Age 22.4 ±5.4; Experience 8.1 ±5.2 years), 7 male semi-elite (Age 20.6 ±2.4; Experience 4.9 ±2.3 years) and 5 female semi-elite bowlers (Age 20.6 ±4.0; Experience 5.8 ±1.3 years). This number of elite and semi-elite participants represented nearly the entire population of bowlers in the Malaysian senior and back-up national teams.

As for the non-bowlers group, the participants comprised of 33 randomly chosen first and second year undergraduate students that were not involved in any competitive sport. There were 14 male students (Age 22.0 ±1.6) and 19 female students (Age 22.6 ±1.3).

Participants received a clear explanation of the study, including the risks and benefits of participation, and written consent (or parental consent for participants under the age of 18 years) was obtained before participants were permitted to participate (see Appendix 2). All participants reported that they were injury free on the data collection dates. There were no invasive procedures used throughout the course of the data collection.

3.1 Physical Measurement Methods

Anthropometric and Strength Measurement Equipment

For length and breadth measurements, one medium and one larger unit of calibrated Lafayette Sliding Anthropometer (Lafayette Instrument Company, USA) was used. Height was taken using a SECA Stadiometer (SECA Gmbh, Hamburg) while weight was measured using a calibrated balance weighing scale (DETECTO, Missouri). Arm span measurement was taken using a fiberglass tape that was attached to the wall.

For strength measurements, the multi-head universal Lafayette Load Cell, Model 01163 Manual Muscle Tester (Lafayette Instrument Company, USA) was used. An additional steel strength apparatus was constructed in the lab to aid in isolating certain hand segments during the strength tests. A pilot trial of 20 volunteers yielded a concurrent validity correlation coefficient for this setup, tested against correspondingly well known strength tests of 0.96, 0.94 and 0.75 (see Appendix 3). While the correlation coefficient for test retest reliability of three of the test used in this study were 0.98, 0.97 and 0.98.

Test Protocol

Choice of tests was based on literature of other throwing events and thorough discussions with the national coaches (Cheah, 2009). It was important to note that, testing was constrained by the time allowed, which was a maximum of two hour per bowler to complete the measurements as well as conduct the motion analysis.

The data collection was done over a five day period. Each participant only came for either one of the days and spent between 40 to 60 minutes going through the tests. Participants started off by filling up a personal background form as well as a consent form. All participants had neither major illnesses nor major injury and were able to continue to participate in the study.

Firstly, participants were instructed to change into their respective bodysuits. Anthropometric measurements were taken, followed by the set of isometric strength tests. Participants were then asked to wear their ankle level socks and shoes, their body wiped down of any sweat and had reflective markers placed on them. Lastly, when all measurements and tests were completed, the video capture process for each participant commenced.

3.1.1 Anthropometric Test Procedures

Participants were subjected to ten anthropometric measurements which were height, weight, seated height, biiliac and biacromial breadth, armspan, dominant side's upper arm, lower arm, hand length and tibial length. Circumference and skinfold measurements were not measured. Leg length was calculated by subtracting seated height from height, from there the ratio of seated height to leg length (SH:LL Ratio) was generated. Anthropometric data collection methods were as per convention listed by Lohman, Roche, and Martorell (1991). Three non-consecutive trials were taken for each site and the median score was used in the analysis. Participants were measured whilst wearing only a body suit, and where appropriate, the suit was pulled back so as to take direct measurements from the skin.

Only one tester collected the anthropometric measurements throughout the study. This individual was trained a month in advance. A pilot trial by repeatedly measuring 20 volunteer students resulted in an acceptable intra-class correlation coefficient for test-retest reliability and typical error of measurement for tibial length, armspan, hand length and biiliac breadth of 0.94, 0.98, 0.96, 0.94 and 0.6%, 0.2%, 0.8%, 1.0%, respectively.

Height

Measurement was taken using a stadiometer that was attached to a square, vertical concrete beam that was approximately 30 cm wide. While barefooted, participants stood with their back against the beam, heels close together, hands freely hanging at side with the palms facing the thighs and the head and eyes facing straight ahead. The heels, buttocks and scapula were touching the beam and weight was distributed evenly on both legs. Participants were then instructed to inhale and to hold their breath while maintaining an erect posture. Measurement was taken while applying sufficient pressure on the stadiometer to compress the hair. Height was recorded to the nearest 0.1 cm.

Sitting Height

The same apparatus as the Height measure was used but with the addition of a 50 cm high square box. The subject sat with legs stretched to the front on the box that was lined up against the beam, with the buttocks and scapula touching the beam. Hands were rested on the thigh and the head and eyes were facing forward. Participants were then instructed to inhale and to hold their breath while maintaining an erect posture. Measurement was taken while applying sufficient pressure on the stadiometer to compress the hair. Sitting Height was recorded to the nearest 0.1cm.

Weight

Each participant stood still on the centre of the scale with the bodyweight distributed evenly on both feet. Measurement was recorded once the meter's scale stabilised. The participant got off the scale and the process was repeated. Weight was recorded to the nearest 0.1 kg.

Arm Span

A fiberglass tape was mounted horizontally to a flat surface of a wall, 160 cm from the floor. A triangular ruler was used to accommodate for height differences between subjects and to mark length. Each participant stood with the feet together and the back against the wall. Their arms were outstretched laterally and maximally at about shoulder height while in contact with the wall and with palms facing forward. Adjustment to standing position was needed to ensure the tip of the middle finger (excluding fingernail) of the right hand was exactly at the zero end of the tape. In addition, the tip of the middle finger of the left hand was touching the ruler. The arms needed to be slightly abducted/adducted to find the longest reach. The position of the ruler on the tape was then recorded to the nearest 0.1 cm.

Tibial Length

The direct length measurement method was used. The participant sat down with the leg of interest crossing over the opposite knee. The proximal end of the medial border of the tibia and the distal tip of the medial molleolus were marked. The anthropometer was aligned so that each blade was applied to the landmark markings and the shaft was parallel to the long axis of the tibia. Reading was taken to the nearest 0.1 cm.

Upper arm (Shoulder-Elbow) Length

The participants stood erect with their weight evenly distributed on both feet. The shoulders were drawn back and upper arm hanged loosely at the side. Both elbows were flexed to place the forearm and hands in the horizontal plane parallel to each other. The shaft of the anthropometer lined up parallel to the upper arm and the fixed ended blade was in firm contact with the superior lateral aspect of the acromion. The sliding blade was moved to be in firm contact with the posterior surface of the ulna olecranon process. Reading was taken to the nearest 0.1 cm.

Lower arm (Elbow-Wrist) Length

The participants stood erect with their weight evenly distributed on both feet. The shoulders were drawn back and upper arm hanged loosely at the side. Both elbows were flexed to approximately 90 degrees with palms facing medially and fingers fully extended. The shaft of the anthropometer lined up parallel to the forearm and the fixed ended blade was in firm contact with the most posterior point overlying the olecranon. The sliding blade was moved to be in firm contact with the most distal palpable point of the styloid process of the radius. Reading was taken to the nearest 0.1 cm.

Hand Length

The participants stood relaxed with the forearms extended horizontally. The hand and fingers were extended and facing upwards. The shaft of the anthropometer lined up parallel to the longitudinal axis of the hand and the fixed ended blade was in firm contact with the most distal palpable point of the styloid process of the radius. The sliding blade was moved to be in light contact with the flesh tip of the middle finger. Reading was taken to the nearest 0.1 cm.

Biacromial Breadth

The measurement was taken from the rear while the participant stood erect, heels together and hands loosely hanging at the side. The participant was in a relaxed state, with the shoulders downwards and slightly forward to get the maximal reading. Each end of the anthropometer blade was pressed firmly on the most lateral border of acromial process on both shoulders, and the shaft parallel to the line formed between the two processes. Reading was taken to the nearest 0.1 cm.

Biiliac Breadth

The measurement was taken from the rear while the participant stood erect with feet about 5 cm apart (which prevented swaying). The arm was folded at the chest. The anthropometer blades were brought into contact with the iliac crests so as to find the maximum breadth. Firm pressure was applied with the anthropometer slanted at a 45 degree angle. Reading was taken to the nearest 0.1 cm.

3.1.2 Isometric Arm Strength Test Procedures

Peak isometric strength test was chosen for this study, and seven variables were measured - finger pinch between the index to thumb, middle finger to thumb, third finger to thumb, arm flexion (at approximately 90 degrees), wrist flexion (at full extension), forearm/wrist internal rotation (FIR) and forearm/wrist external rotation (FER) (Figure 3.1). Three non-consecutive trials were done for the dominant side and participants kept their in-active hand behind their backs. The maximum score was used in the analysis. All scores were normalised to body weight.

Finger Strength (flexion/pinch)

Participants stood in a relaxed position with the elbow flexed to 90 degrees. They then gripped the unit with the thumb firmly at the back and the tip of the index finger on the unit's sensor, as in a pinching position. Once ready, participants pinched as hard as possible and relaxed the grip once the maximal capacity was reached. The machine records the peak force for each try. The test was done for the index finger-to-thumb, middle finger-to-thumb and fourth finger-to-thumb only. Force was recorded to the nearest 0.1 N.

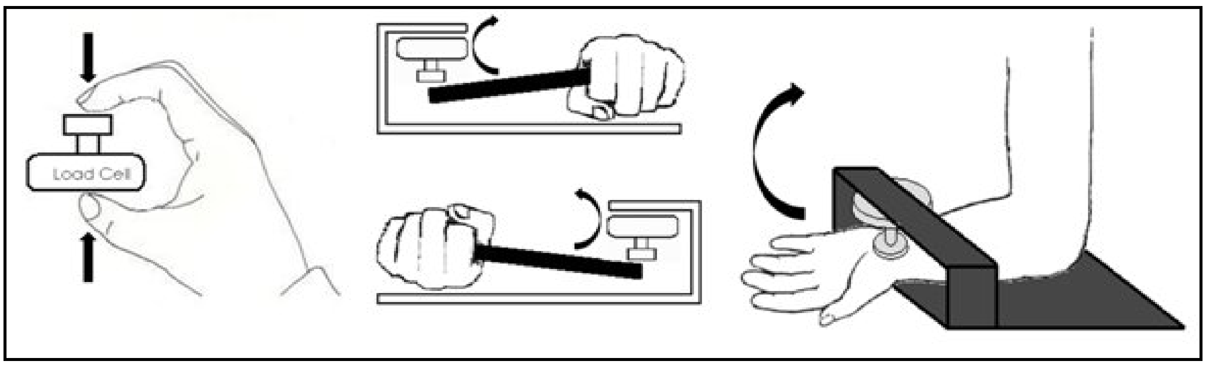


Figure 3.1: Finger pinch, internal/external rotation and lower arm flexion test

Hand Strength (flexion/extension)

The participants stood erect on the left side of the apparatus and had the right forearm resting on it. A velcro strap was wrapped exactly behind the styloid process of the radius and another one near the elbow crease to isolate the wrist joint. The hand placement was adjusted so as to have the metacarpal-phalange joint of the middle finger resting on the sensor. Once ready, participants flexed the wrist as hard as possible and relaxed once the maximal capacity was reached. Peak force for each try was recorded. Force was recorded to the nearest 0.1 N.

Wrist Strength (internal/external rotation)

The participants stood erect on the left side of the apparatus and had the right forearm resting on it. A velcro strap was wrapped near the elbow crease to assist in holding down the forearm. One end of a 30 cm aluminum bar was held comfortably by the right hand, while the other end was placed on the unit's sensor. The bar was positioned perpendicular to the forearm. Once ready, the participants tried to internally rotate the forearm-wrist as hard as they could and relaxed once the maximal capacity was reached. Peak force for each try was recorded. The test was also done for external rotation, using the same procedure but changing the position of the load cell. Force was recorded to the nearest 0.1 N.

Lower Arm (flexion)

The participants stood erect on the left side of the apparatus and had the right forearm resting on it. The hand placement was adjusted so as to have the scaphoid-radius joint resting on the sensor. Once ready, participants flexed the forearm as hard as possible and relaxed once the maximal capacity was reached. Peak force for each try was recorded. The process was repeated for the other hand, before repeating the same hand for the second and third trials, respectively. Force was recorded to the nearest 0.1 N.

3.2 Motion Analysis Methods

Test Equipment

The main equipments used in this study revolved around the Kwon3D software. As with most biomechanics research, equipment cost was a limiting factor. Therefore, a majority of the hardware support equipment used for the software was custom made at the Biomechanics Laboratory, located in the Sports Centre, University of Malaya. The bulk of the grant funding was spent on the software and for the Basler high speed cameras.

Kwon3D Motion Analysis Software

Kwon3D (Visol Inc, Korea) is a flexible motion analysis system that is able to capture synchronised 100 frames per second digital video simultaneously from multiple cameras. There was not a need for different recording and capturing processes because it utilised digital cameras connected directly via IEEE1394 (firewire) from the host computer. Stream data from the cameras were stored directly onto the main computer hard drive (in this case, one hard drive per camera) in real time.

This arrangement also allowed the host computer to control the cameras, hence the synchronised capturing which eliminated the need for manual or audio gen-locks later on in the analysis process. It allowed capturing to be done using normal video input with normal background lights or as in the case of this study, infra red (IR) images utilising IR lights and Basler cameras that had its IR filter removed.

Captured footage was digitised directly in the software, using the semi-auto marker tracking option. 3D coordinates were then computed by the system using the Direct Linear Transformation (DLT) method (Abdel-Aziz & Karara, 1971) based on the body model that was defined.

Computer Hardware

The system had two computers, a primary host computer and a secondary slave computer. Both were connected to each other via a Gigabit LAN router. It operated based on Windows XP operating system and was powered by Intel Pentium (R) D 3.00 GHz processors. It had 2 GB of RAM space and equipped with ATI ASUS AX550 graphics cards with 512 MB of HyperMemory. The main unit was also installed with a National Instruments (National

Instruments, Austin, Texas, USA) PCI6601 Data Acquisition Board. Both the units also had Gigabit Network Adapters for high speed data transfers between them.

Using high speed cameras capturing directly to the hard drives meant that there was an enormous amount of data being transferred and stored at any given time. A computer motherboard has only two PCI slots to house the IEEE1394 Firewire PCI adapters, and these slots have a limited bus-speed and bandwidth which can only handle a certain amount of data at a time. Therefore, to be able to stream 100 Hz raw video, only one camera could be connected to one adapter, meaning that one computer can only accommodate two high speed cameras.

The Kwon3D software was installed in the primary unit, while the secondary computer had a software called Visol MultiNet Express that allowed it to capture from the two cameras and transfer the data directly to the main unit via the Gigabit LAN. The main computer was also the storage centre whereby, on top of its own systems' hard drive it also had four additional 320 GB drives, one for each camera. All the computer hardware was self-assembled in the biomechanics laboratory.

<u>Basler High Speed Cameras</u>

There were four high speed cameras used in this study, the Basler A602fc, acquired from Basler AG (Ahrenburg, Germany). These units had ½ inch CMOS sensors utilising global shutter and were able to capture at 100 full frames per second. The Kwon3D software was able to control the capture rate of the cameras at 30, 60, 80 or 100 fps. This study used the maximum capture rate of 100 fps. The cameras' power was supplied by the IEEE1394 bus/cables. Via the IEEE1394, the software was also able to control the cameras' gain, brightness and exposure time of each individual camera. In addition, the Basler 602fc also had LAN RJ45 ports that accepted trigger signals from the Timing Generator via two wires in the LAN cables. This in turn allowed synchronised video capture from all four cameras. In short, there were only two cables that ran to each camera, the IEEE1394 (Firewire) for video data as well as the camera power and controls as well as the LAN RJ45 cables for timing triggers and modified power supply for the IR LED lights.

Throughout the data collection of this study, a locally sourced C-mount 4.5-10 mm zoom lens with 1:1.6 scale was used for the Basler cameras. It had a work space range of between 5 to 10 meters, which was ideal for use in the bowling alley. The IR lens filter from each camera was also physically removed to allow for better quality video under IR environment. The cameras were used in conjunction with custom made tripods. It was made using 1¾ inch steel tubing and was able to be adjusted from a height of 1.5 to 2.5 m. It also had a combination of closed cell foam and rubber dampeners at the bottom of each leg to help dissipate vibrations that occur on the bowling alley floor. The unit was self-fabricated in the laboratory.

Timing Generator

The software was able to synchronise all the cameras for simultaneous video capture, but it needed a hardware interface, that is, a timing generator (Figure 3.2). The device generated identical timing signals for each camera.

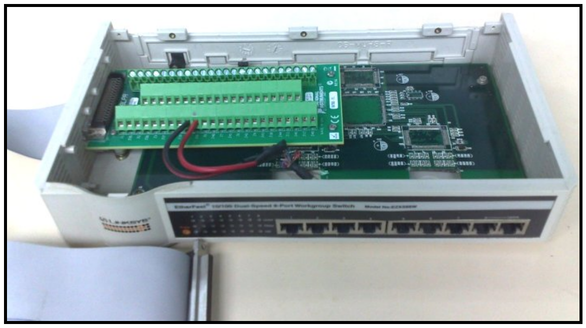


Figure 3.2: Self-fabricated timing generator

The source of the signal came from the National Instruments PCI6601 card located in one of the PCI slots of the main computer. Meanwhile, the timing of each signal was based on the video capture rate that was set in the Kwon3D software. The PCI6601's signal was then transferred to an external 'distribution box' which was able to transmit the signal via individual RJ45 LAN cable to each camera. This box unit was also hand constructed in the laboratory by modifying a donor LAN router to host a National Instruments CB-68LPR I/O connector block.

Reflective Markers and Body Suit

In line with most modern motion analysis capture environment, reflective markers were used in this study to make semi-auto digitisation possible. The markers used were 15 mm in diameter and were hand made using polystyrene that was wrapped in 3M (3M Corporation Minnesota, USA) reflective tape. A 20 mm flat base, made using a thick plastic button, was also added that made placement on the subject easier.

To aid in locating the markers, participants were made to wear black body hugging Arena bodysuits (Arena, Italy). The body hugging nature of the suit makes it more akin to placing reflective markers directly on to the skin. It came in four different sizes for men and women, respectively. A black swim cap was also used to aid the placement of a marker on the vertex.

Infra Red Lighting System

Infra Red (IR) LED lights was chosen instead of using powerful halogen lights because the brightness and glare of the halogen lamps distracted the bowlers as was found in the pilot trials. These halogen lamps with their 500 watts bulbs would have also needed a direct power supply from the mains and four lamps would have meant four additional thick cables running across the bowling alley test site. IR light meanwhile was less obtrusive and it required less power.

The IR lighting system was self-constructed in the laboratory using a combination of large (8 mm) and small (4 mm) IR LED's that were soldered on a printed circuit board (Figure 3.3). The board had a large opening in the middle for the camera lens to pass through as well as mounting holes so that it could be securely mounted to the camera.

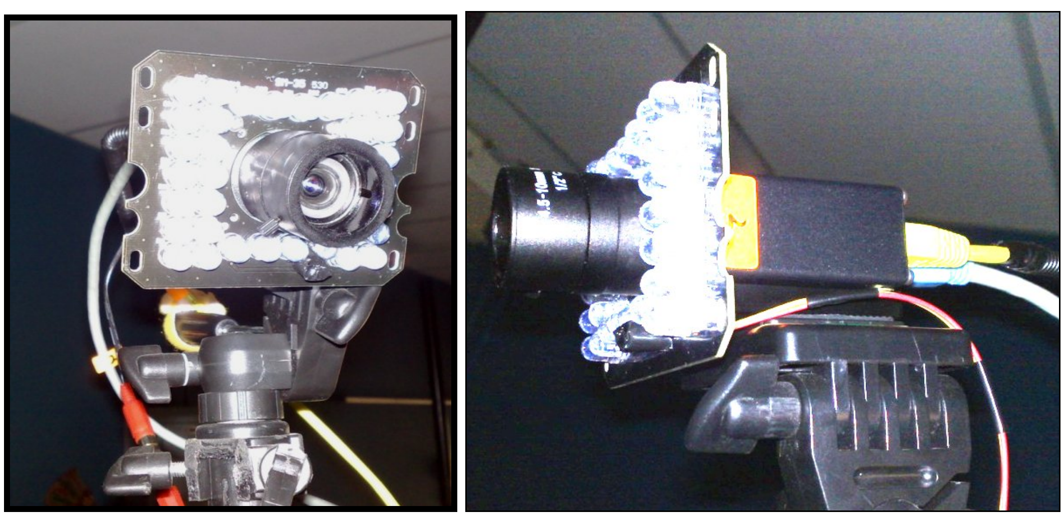


Figure 3.3: Basler cameras with self built IR lights and mounts

Each camera had a total array of 36 large and 24 small IR LED's mounted on its frame but only consumed a total of less than 2 amp per set. These were powered via an external 10 amp AC/DC converter that was connected via timing generator's distribution box. As the timing signal was only transmitted using two wires out of eight in the RJ45 LAN cable, the remainder of the wires in the cable was available to use for power supply. This arrangement greatly reduced the logistical issue of routing additional power cables.

Portable Calibration Frame

A 2 m high by 2 m long by 1 m wide frame was used for every calibration frame capture of the study. It was constructed with the intent of making it portable, therefore it could be assembled or disassembled easily. It was made of aluminum tubes (15 mm in diameter) and connector blocks (Figure 3.4). A total of 33 tubes and 18 connector blocks were used in the frame. There were 15 mm strips of 3M reflective tape wrapped around the upright bars that was placed 20 cm, 50 cm, 80 cm, 120 cm, 150 cm and 180 cm away respectively from the mid-point of the bottom connector ball. In total there were 36 markers on the calibration frame. It also had an adjustable base under each bottom connector block to accommodate uneven surfaces.

With the current hardware/software setup, the RMS reconstruction error values in the x, y and z axes for the calibration frame were 3.9, 3.8 and 4.1 mm respectively.

Marker Placements

For the whole body model that was constructed for the delivery analysis, there were 21 reflective markers placed on the participants (Figure 3.5). The markers were at:

- Vertex of the head [x 1]
- Chin (below the mental foramen) [x 1]
- Lateral tip of the acromion [x 2]
- Anterior Superior Illiac Spine (ASIS) [x 2]
- Posterior Superior Illiac Spine (mid-point between left and right) [x 1]
- Elbow (between lateral epicondyle and olecranon) [x 2]
- Wrist (styloid process of the ulna and radius) [x 4]

- Hand (distal end of the middle metacarpal and placed on the handguard if one was used) [x 2]
- Knee (femur lateral epicondyle) [x 2]
- Ankle (lateral and medial malleolus) [x 4]

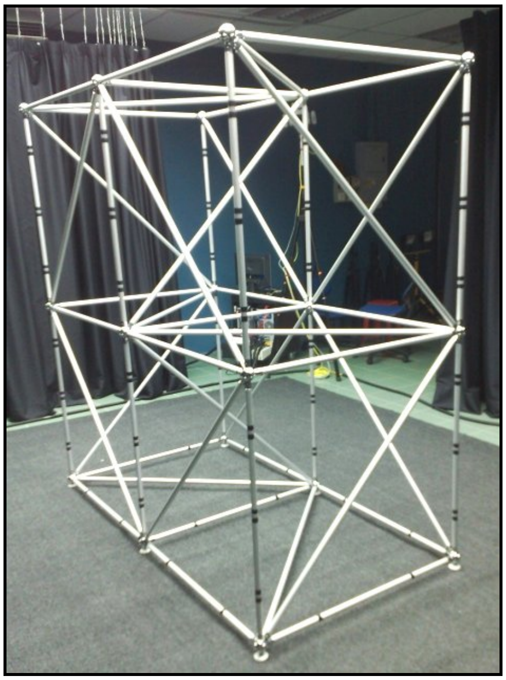


Figure 3.4: Calibration frame

Figure 3.5: Marker placement

Markers were not placed on medial side of the knee because during the pilot trials it came off when the bowlers' leg crossed. Reflective markers were also not placed on the medial side of the elbow as it brushed the side of the body during the down swing. All the above markers were recognised as primary digitising points in the software. Based on the constructed body model in Kwon3D, secondary points were also defined. These secondary points were:

- Wrist Joint Centre (mid-point between the two wrist markers) [x2]
- Ankle Joint Centre (mid-point between the two ankle markers) [x2]
- Hip Joint Centre (Tylkowski Method) [x2]

The estimation of hip joint centre used in this study was originally suggested by Tylkowski, Simon, and Mansour (1982) and had the ratio values adjusted by Bell, Pedersen, and Brand (1990). The mediolateral, anteriorposterior and superiorinferior positions of the hip joint in the pelvis were functions of the inter-ASIS width (W in Figure 3.6): 0.14W medial, 0.19W posterior and 0.30W inferior to the corresponding side ASIS.

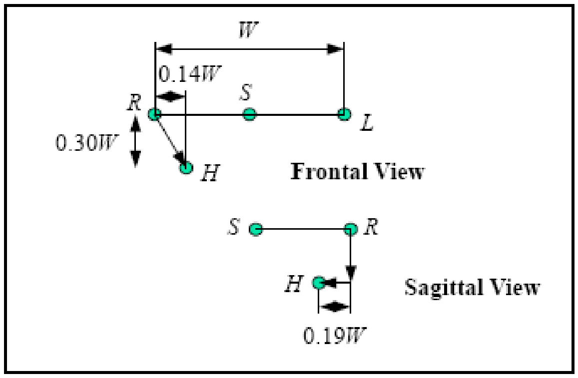


Figure 3.6: Hip joint centre (Tylkowski method)

Camera Placement

There were four cameras used in this study. Each was mounted on a secure tripod approximately 2.2 m high. Camera 1 faced down at about a 30 degree angle while the rest of the cameras were at a 45 degree slant. All the relevant cabling was routed around the alley being used and none cut across the alley or interfered with the bowlers initial steps. Approximate camera placements on the bowling alley are as shown in Figure 3.7.

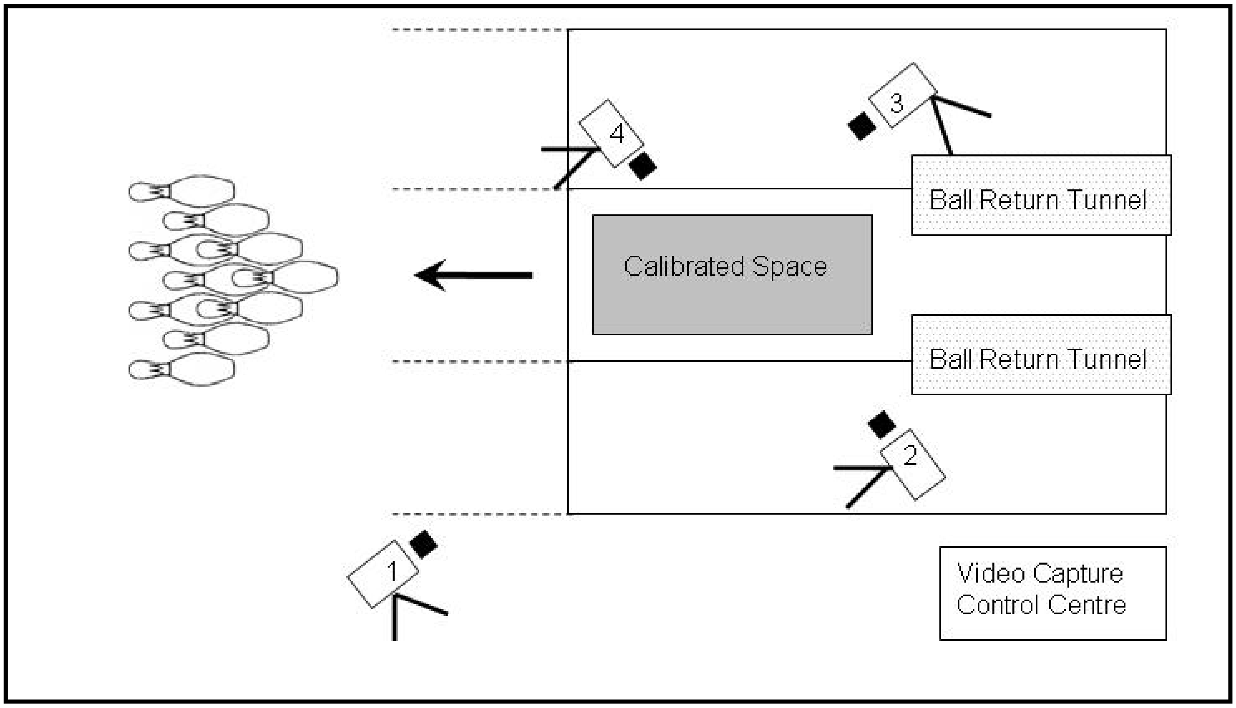


Figure 3.7: Camera placement at the bowling alley

<u>Video Capture Procedures</u>

Prior to each day's session, the calibration frame was brought onto the test alley and cameras were adjusted to have an unobstructed view of the markers as well correct focus and gain. The exposure time was set at 1/500 s for all cameras while gain varied for each camera and was adjusted accordingly in order to have the best reflection from the reflective markers. Two calibration frame trials were recorded before the frame was removed. There was also a fixed marker placed on the floor, visible throughout the calibration and all trials.

Participants were asked to warm-up by bowling 10 balls at their own pace to get accustomed to bowling with the bodysuit and markers under dimmer light conditions. This process took between 5 to 10 minutes. Participants used their own bowling shoes and their own bowling ball. Participants then indicated when they were ready to commence the tests.

Only first ball deliveries were captured (pins were reset after every trial), and subjects were instructed to try to bowl with their best effort, with the same technique in every trial. More specifically, this meant that they were told not to change their bowling style midway. Participants were also asked to indicate after each trial whether there were any problems with that particular delivery, if so then that specific trial would be repeated. There were seven trials conducted, but video capture was only done for the last four trials. The participants did not know which trial was being recorded. The first three trials helped in getting them familiarised with bowling under the scrutiny of the cameras and testers.

Trials were recorded at 100 frames per second for 3.5 seconds from their first initial movement, with the capture start controlled manually by the tester manning the main computer. The start was initiated as the participant took the first step.

Digitising

The bowling motion was distinguished by three key events (Figure 3.8), which were:

1. Top of Back Swing (TBS) - the start of the motion of interest,
2. Front Foot Strike (FFS) - the point at which the sliding foot first touched the ground,
3. Ball Release (REL) - the frame at which the ball leaves the hand.

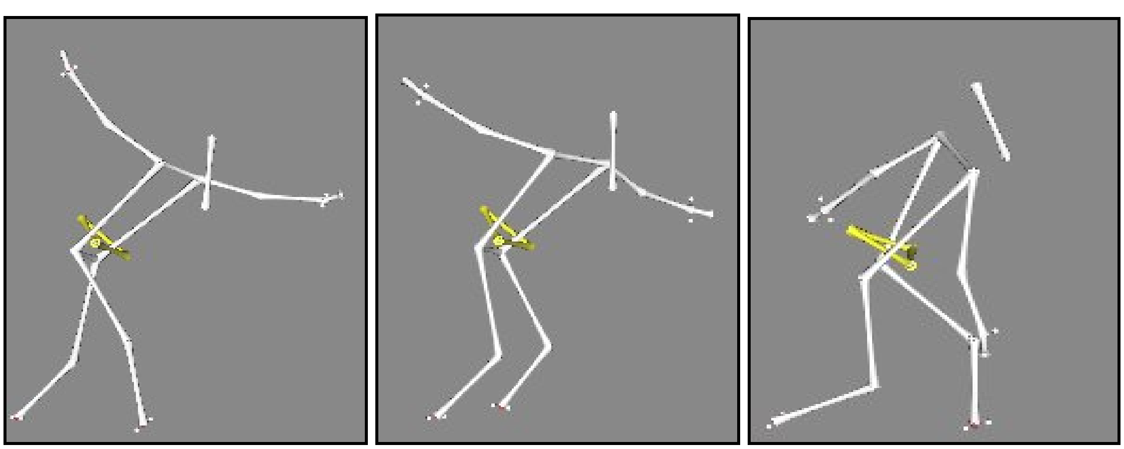


Figure 3.8: Key events – TBS, FFS and REL

Capture footage from all cameras were trimmed five frames prior to the TBS and five frames after the bowlers reached the top of their follow-through. Kwon 3D semi-auto digitising function was carried out utilising a user defined body model with the listed primary and secondary points. Even though on auto mode, digitising was done frame by frame to scrutinise for error in marker tracking as well as to identify markers that were obscured or had low reflection. Manual digitising was done for the ball as there were no markers placed there. Digitising was done by the same research assistant throughout the study. Interpolation function for missing markers was used only when there were less than two cameras in view of a particular marker at a given point in time. Interpolation frequency was set at 100 Hz, the same as the camera capture rate.

Data Reduction

Raw marker point position data was filtered for random noise, marker skin movement artefacts as well as camera/tripod vibration. Filtering was done using a low pass filter, the second order digital Butterworth filter and the cut-off frequency was set at 6 Hz. As the total frame for each trail varied, the variable-time data was time normalised from TBS to REL (percentage of cycle, with 101 data points) to facilitate comparisons between trials and between subjects.

Research Variables

The primary dependent variable is the Bowling Score Average (BS_{ave}) which was tabulated from three major tournaments nearest to the data collection date**.**

In terms of independent kinematic variables, for linear motion, means of four trials position-time in X (lateral), Y (anterior-posterior) and Z (superior-inferior) directions were used with subsequent velocity-time and acceleration-time data. Discrete data points of interest such at

TBS, FFS, REL, maximum, minimum and range as well as the corresponding temporal data was extracted (Figure 3.9). While for kinematic angular motion, only angles in the sagittal plane were used, whereby the 3D position of joint markers from corresponding linked segments were projected onto the 2D sagittal plane to generate the respective joint angles.

In terms independent variables used for the within-subject inter trial movement variability analysis; standard deviation (SD) at discrete points in time of the individuals' four trials was used as the indicator for absolute variability (Figure 3.10).

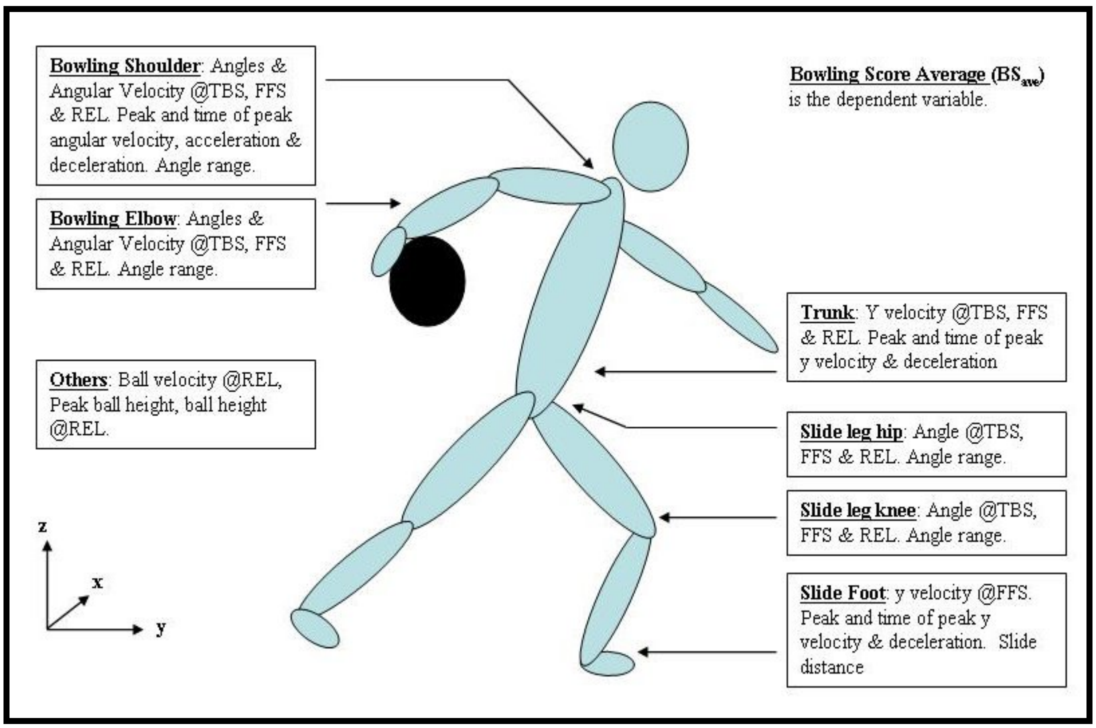


Figure 3.9: Variables for kinematic analysis

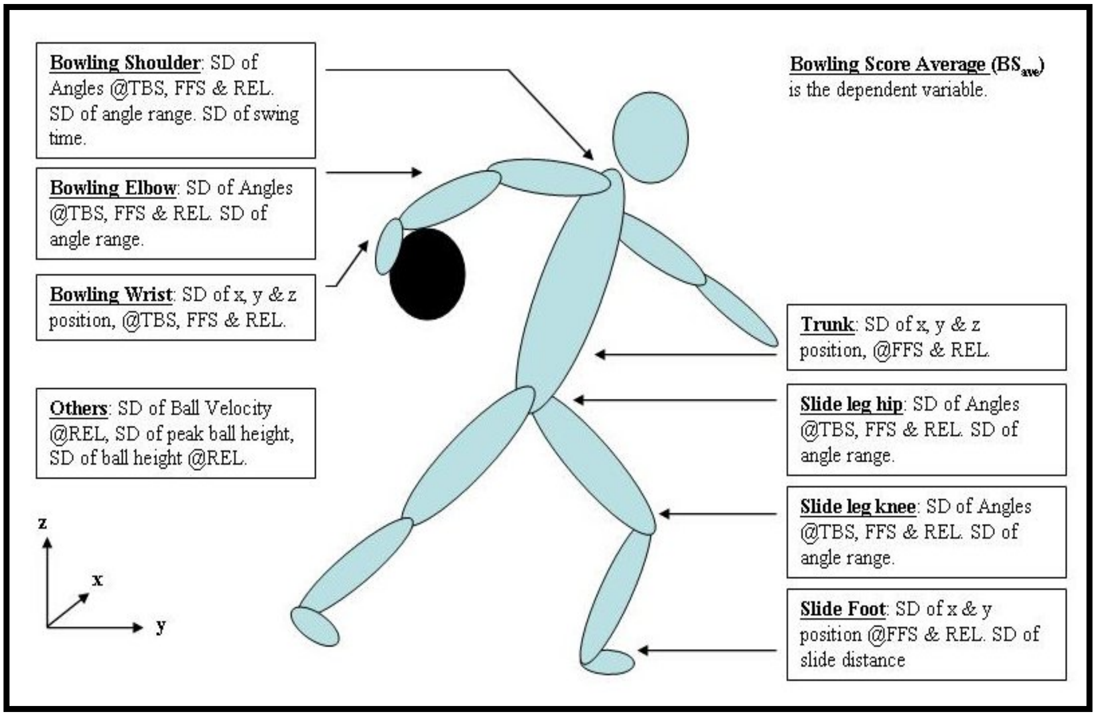


Figure 3.10: Variables for variability analysis

3.3 Measuring Segment Contribution

Peak horizontal linear velocities of joint markers were used as representation of the particular segment contribution towards the final linear ball velocity at release. Peak linear horizontal velocities of the hip marker (representing the lower limb contribution), shoulder marker (representing the upper body contribution), elbow marker (representing the upper arm contribution), wrist marker (representing the lower arm contribution) and metacarpal marker (representing the hand contribution) were extracted. Meanwhile, the difference between the metacarpal marker velocity to the final ball velocity at release was considered as contribution from the fingers.

3.4 Statistical Analysis Methods

Data analysis was conducted using the SPSS 16.0 statistical software package. Means and the range for all of the independent variables were determined. Differences between elite, semi-elite as well as non-bowlers (only for anthropometric and strength measurements) were compared using a two-way (group*gender) analysis of variance.

For anthropometric and strength variables, if there was a significant main effect for group, a Tukey's HSD post hoc test was conducted. In addition if there was a significant interaction effect, separate one-way ANOVA for males and females, respectively, were carried out to differentiate the elite, semi-elite and non-bowlers within each gender.

Meanwhile, for all other variables (kinematic and movement variability) which had significant interaction effects, a Mann-Whitney test was performed to determine if there were group differences within the males and females, respectively. Furthermore, the Pearson product moment correlation coefficients were also examined as a secondary analysis to explore the respective variables' relationship to BS_{ave} so that data interpretation is enhanced.

The use of gender in all analyses was a secondary factor, with minimal emphasis on inter-gender comparisons. Rather, emphasis was on inter-group comparisons conducted with gender pooled, and inter-group comparisons carried out gender by gender.

The objective of this study was to determine the critical parameters in ten pin bowling delivery that contributed to bowling performance. Consequently, a discriminant analysis was conducted to highlight variables that best discriminated the groups – these variables were considered the 'critical parameters'. Clearly, many comparisons and correlations were performed in an aggressive statistical approach to control Type II errors and to identify important independent variables, inadvertently resulting in a probably larger familywise Type I error rate. Because of this, and the limited sample size, it is important to regard the findings of this study as essentially exploratory and descriptive in nature.

CHAPTER FOUR:
RESULTS AND DISCUSSION

Chapter 4: Results and Discussion

4.1 General Bowling Performance

4.1.1. Results

The descriptive bowling performance results for the elite and semi-elite bowlers are shown in Table 4.1. Although the bowlers were grouped based on their BS_{ave}, the independent-samples t-test revealed that overall, there were no significant differences between the males and females in terms BS_{ave}, $t(28) = -0.11$, $p = .91$ and competitive experience, $t(28) = 0.847$, $p = .404$. While for ball release velocity, there were no significant differences between gender $t(28) = 1.674$, $p = .105$ as well as between groups $t(28) = 1.053$, $p = .301$.

Table 4.1: Descriptive bowling performance results (reported as Mean ±SD)

Variable	Elite	Semi-Elite	Elite (M)	Elite (F)	Semi-Elite (M)	Semi-Elite (F)
Bowling average (pin falls)	213.23 ±6.80	181.84 ±9.36	213.80 ±7.69	212.53 ±5.92	180.67 ±8.18	182.29 ±11.78
Competitive experience (years)	9.83 ±4.55	5.25 ±1.91	11.20 ±3.71	8.13 ±5.17	4.86 ±2.27	5.80 ±1.30
Ball release velocity (m/s)	8.00 ±0.42	7.78 ±0.71	8.08 ±0.47	7.89 ±0.35	8.02 ± 0.69	7.45 ±0.67

4.1.2 Discussion

The exploratory analysis were guided by a number of factors including (but not limited to) national/state coaches feedback, coaching manuals and reference from other similar underarm pattern sports. The underlying assumptions for group comparisons based on playing level was that there should be no significant difference in terms of performance between male and females bowlers. This assumption was confirmed in this study whereby there was no significant difference in terms of BS_{ave} between genders. In contrast, Tan, Aziz, and Teh (2000) found that elite male bowlers had significantly higher scores than the female. Though, in the particular study they had 50% more male samples than females and the samples also had a lower mean bowling average compared to this study. Earlier in that decade, Thomas, Schlinker, and Over (1996) summed that since men and women of the same overall bowling average in their study had similar psychological and psychomotor skill profiles, ten-pin bowling should be considered a gender-neutral sport. This latter proposition seems rather appropriate in light of the dearth of published literature on this simple issue.

The mean $BS_{ave}$of 213 for elite and 181 pin falls for semi-elite over three tournaments closest to the data collection date highlights that both the groups consists of high calibre bowlers. As this point in time, it was the highest level of bowlers used in any published study. Comparatively, Thomas, Schlinker, and Over (1996) recruited league bowlers ranging from 112 to 186 pin falls, Tan, Aziz, and Teh (2000) utilised elite bowlers with a mean bowling average of 193 pin falls while Harris (2008) used elite bowlers with a mean of 200 pin falls and novices with a mean of 103 pin falls.

In relation to ball release velocity, even though there were differences in overall ball release velocities between male (8.05 m/s) and female (7.72 m/s) bowlers, this difference was not statistically significant. There were also no significant difference in ball velocity between the elite (8.00 m/s) and semi-elite (7.78 m/s) groups. In addition, this study found no significant relationship between ball release velocity and BS_{ave}. Although it is common notion (Benson, 2000; Strickland, 1996) to equate the modern game in bowling as being a power game, this apparent lack of relationship suggested that there is possibly a ball velocity threshold – after which any increase in ball velocity does not necessarily equate to better scores. The scatter plot in Figure 4.1 indicating that these high level bowlers released the ball between 7.5 to 8.5 m/s.

Consequently, the decision to group males and females together based on bowling performance, and to use BS_{ave} as the sole performance indicating dependent variable were deemed appropriate for this study.

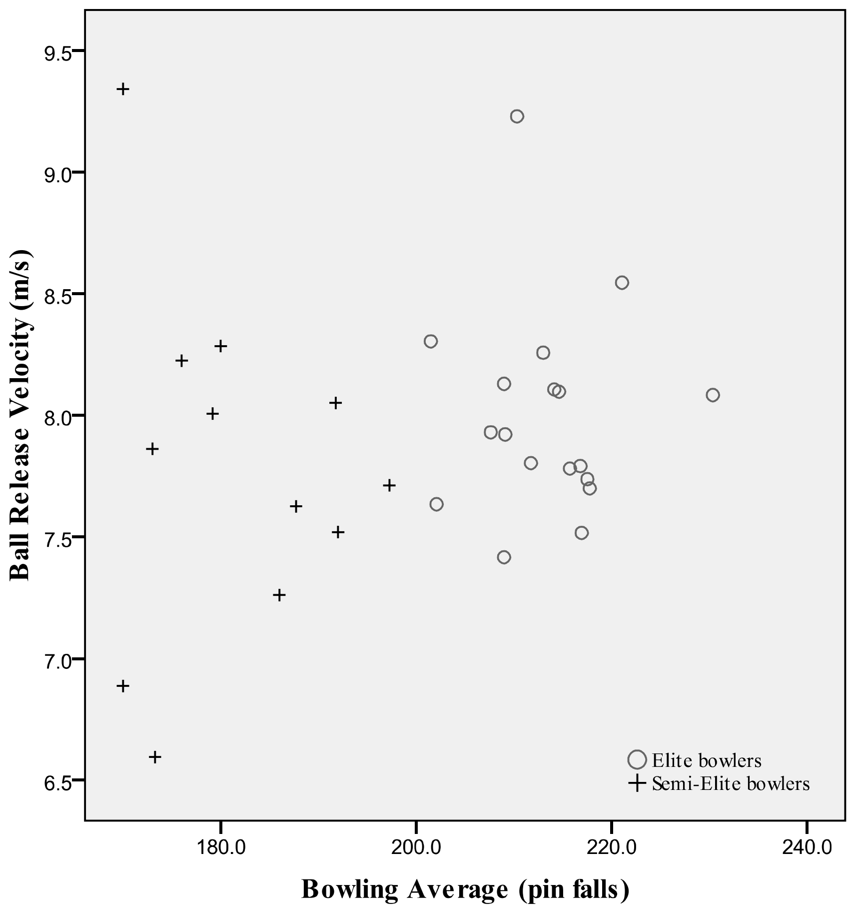


Figure 4.1: Scatter plot of ball release velocity for various bowling averages

4.2 Anthropometry and Strength

4.2.1Results of Anthropometric Comparisons

Means for anthropometric results are presented in Table 4.2. There was a significant interaction effect for SH:LL Ratio. Follow-up analyses using separate t-tests for the three different groups revealed that the SH:LL Ratio for males and females were significantly different only for the semi-elite, t(10) = 5.06, $p < .001$, and non-bowlers groups, t(31) = 3.16, $p = .004$. There were no group differences within each gender.

There were significant main effects for gender in height, weight, tibial length, armspan and hand length. In addition, there were significant main effects for groups in terms of weight, tibial length, armspan and hand length. For body weight, the elite bowlers (M = 68.7± 12.9 kg) were heavier than the non-bowlers (M = 58.0± 11.2 kg). Both elite (M = 38.2± 2.2 cm) and semi-elite bowlers (M = 38.2± 3.2 cm) had longer tibial length than the non-bowlers (M = 35.7± 2.1 cm). Similarly, elite (M = 172.1± 8.1 cm) and semi-elite (M = 172.6± 12.9 cm) bowlers had longer armspan compared to the non-bowlers (M = 164.0± 9.7 cm). For hand, elite bowlers (M = 18.6± 1.0 cm) hands were longer than non-bowlers (M = 17.6± 1.1 cm).

4.2.2 Results of Isometric Upper Limb Strength Comparisons

Means for strength measurements are presented in Table 4.2. There was a significant interaction effect for arm flexion. Follow up using a separate one-way ANOVA for each gender revealed that there was a significant difference for the male group, $F_{(2,57)} = 8.88$, $p = .001$, whereby the male elite bowlers had significantly higher arm flexion scores compared to the male non-bowlers, but differences between female elite bowlers and female non-bowlers were not detected. There was a significant main effect for gender whereby the males had higher scores in the pinch strength between theindex to thumb and middle finger to thumb as well as for arm flexion, wrist flexion, FIR and FER. Meanwhile, there was also a significant main effect for group FIR. The elite bowlers (M = 6.17 ±2.28 kg) had stronger FIR compared to non-bowlers (M = 4.35 ±1.42 kg).

4.2.3 Relationship to Bowling Average

The bivariate correlation analysis showed that none of the anthropometric and strength variables had any significant ($p>.05$) correlation with bowling average. Table 4.3 shows the Pearson product-moment correlation coefficient values for all anthropometric and strength.

4.2.4Discriminant Analysis ofPhysical Attribute Variables

Firstly, the selection of variables to be included in the discriminant analysis was based on whether there was a significant difference between groups for the specific variables. As a result, weight, tibial length, armspan, hand length, arm flexion and FIR were short listed (refer to Table 4.2). Secondly, to adhere to the multicolinearity assumption, shortlisted variables that had high co-correlation ($r > .05$) were omitted. Consequently, only weight, hand length and FIR were used as variables in the analysis. Box's M indicated that assumptions of equality of variance-covariance matrices were met. The discriminant analysis indicated the presence of two functions. The first indicated an emphasis on the strength and mass dimension while the second reflected more on the anthropometric dimension (refer to Table 4.4). Only the first function was significant ($p = .002$), but the model only explains for 28.8% of variation in the grouping variable. The cross-validated classification showed that overall, 54.0% of the participants were correctly classified. Within each group, 55.6% of the elite, 16.7% of the semi-elite and 66.7% of the non-bowlers were correctly placed in their respective groups. There were high ($r > .30$) loadings for all variables in the first function, with FIR being the best predictor.

Table 4.2: Anthropometric and Normalised Isometric Upper Body Strength (%Body Weight) Measures of Elite Bowlers, Semi-Elite Bowlers and Non-Bowlers (reported as Mean ±SD)

	Male			Female		
	Elite	Semi-Elite	Non-Bowlers	Elite	Semi-Elite	Non-Bowlers
Age	23.6 ± 3.9	20.6 ± 2.4	22.00± 1.6	22.4 ± 5.6	20.6 ± 4.0	22.6 ± 1.4
Height (cm) †	170.7 ±8.7	171.8 ±8.3	167.2 ±7.3	162.6 ±4.8	159.0 ±7.2	157.0 ±4.5
SH:LL Ratio* †	1.05 ±0.04	0.99 ±0.03	1.02 ±0.06	1.06 ±0.06	1.10 ±0.47	1.08 ±0.45
Weight (kg) † ‡	69.6 ±12.9	68.0 ±19.9	66.7 ±13.7	67.5 ±13.7	56.6 ±5.4	53.6 ±9.4
<u>Anthropometric Measures</u>						
Tibial Length (cm) † ‡	39.0 ±2.3	40.1 ±2.6	37.2 ±1.8	37.2 ±1.7	35.6 ±1.9	34.5 ±1.6
Armspan (cm) † ‡	176.2 ±7.1	180.5 ±9.0	172.1 ±8.2	166.9 ±6.2	161.6 ±8.5	158.0 ±5.4
Upper arm (cm) +	33.9 ±1.9	34.0 ±2.0	32.7 ±1.8	30.9 ±1.2	29.6 ±1.0	30.1 ±1.3
Forearm (cm) +	28.0 ±1.3	28.6 ±1.6	26.6 ±1.6	26.2 ±1.8	24.7 ±1.1	24.0 ±0.9
Hand Length (cm) † ‡	18.8 ±1.1	19.3 ±1.3	19.4 ±1.1	18.2 ±0.9	17.1 ±0.9	17.0 ±0.6
Biacromial Breadth (cm) +	40.3 ±1.7	39.4 ±3.3	38.8 ±2.0	36.3 ±1.1	35.2 ±1.9	33.6 ±1.5
Biiliac Breadth (cm)	28.0 ±3.8	27.3 ±3.3	27.0 ±1.8	27.5 ±2.8	26.5 ±1.5	26.2 ±1.2
<u>Strength Measures</u>						
Index Finger to Thumb Pinch (%) †	8.46 ±1.49	8.70 ±2.01	7.47 ±1.34	6.42 ±1.24	7.27 ±1.90	6.60 ±1.51
Middle Finger to Thumb Pinch (%) †	7.10 ±1.95	7.33 ±1.85	5.97 ±2.07	6.62 ±1.55	5.04 ±1.11	5.75 ±1.57
Third Finger To Thumb Pinch (%)	4.06 ±1.38	5.22 ±1.45	4.10 ±1.44	3.99 ±1.30	3.71 ±0.84	3.97 ±1.03
Arm Flexion (%) * † ‡	§ 35.31 ±5.16	30.17 ±6.59	§ 26.51 ±4.04	21.40 ±5.12	19.72 ±6.15	20.78 ±5.07
Wrist Flexion (%) †	20.13 ±2.77	18.33 ±3.95	16.46 ±2.42	12.98 ±3.77	13.62 ±3.70	12.54 ±2.52
Forearm Internal Rotation (%) † ‡	7.63 ±1.95	6.05 ±1.23	5.41 ±1.28	4.33 ±0.91	4.10 ±0.86	3.57 ±0.96
Forearm External Rotation (%) †	6.79 ±1.71	6.79 ±1.49	5.95 ±1.31	4.25 ±0.96	3.98 ±1.01	4.34 ±1.03

* Significant interaction effect ($p<0.05$)

† Significant main effect for gender, significant difference ($p<0.05$) between males and females

‡ Significant main effect for group ($p<0.05$)

§ Significant difference between groups ($p<0.05$), from separate one-way ANOVA for males and females

+Upper arm, Forearm and Biacromial breadth were not used in further analysis as it had high (p>0.90) co-correlation with Armspan.

Table 4.3: Correlation matrix between measured variables and performance

Anthropometric Measures	Bowling Average
Standing Height	.022
Body Weight	.199
Seated Height to Leg Length Ratio	.143
Tibial Length	.000
Armspan	-.001
Hand Length	.089
Biiliac Breadth	.083
Isometric Strength Measures	
Index (2nd) Finger to Thumb	-.072
Middle (3rd) Finger to Thumb	.173
Ring (4th) Finger to Thumb	-.221
Arm Flexion	.291
Wrist Flexion	.170
Internal Rotation	.308
External Rotation	.043

Table 4.4: Discriminant function results for anthropometry and strength

	Structure Matrix of Function		Discriminant Function Coefficients
	1	2	UnstandardisedCoefficients
Forearm Internal Rotation	.74*	.04	49.11
Weight	.59*	.04	.06
Hand Length	.58	.79*	-.07
Constant			-4.78

* Largest absolute correlation between each variable and either discriminant function

4.2.5Anthropometry and Strength Discussion

In an effort to identify characteristics that are potentially critical to performance, comparisons between elite bowlers, semi-elite bowlers and non-bowlers were made, and relationships between these characteristics with bowling performance (bowling average score) were investigated. The bowling group was distinguished based on a single performance variable, which was the BS_{ave}.

Although there were no gender differences in terms of bowling performance, there were significant differences between males and females in a number of anthropometric and strength variables. Males were taller, heavier, had longer limbs and had stronger finger pinch, arm and wrist flexion as well as forearm/wrist rotation strength. These results are similar to previous research findings and the common understanding that there are gender differences in the physical characteristics of athletes (Gabbett & Gieorgieff, 2007; Tan, Aziz & Teh, 2000) as well as in the normal population (Wolfe & Gray, 1982).

In terms of group differences for anthropometric variables, the results indicated that bowlers and non-bowlers were quite different. Elite bowlers were heavier than the non-bowlers. In addition, the elite and semi-elite bowlers had significantly longer upper limbs and lower leg length compared to the non-bowling counterparts although they did not significantly differ in stature. A number of other studies had shown that relationships existed between anthropometric characteristics and sports performance. Body mass have been shown to be positively correlated with throwing velocity (Van den Tillaar & Ettema, 2004b) and kicking prowess (Wong et al., 2009). At the same time, longer limbs have been shown to be positively related to better over-arm throwing performance (Pyne et al., 2006). In fact, an early study in ten pin bowling had also found that longer arm span correlated with better bowling scores (Curtis, 1951) but as technique and technology in bowling has changed so much in the past 60 odd years it makes this particular finding rather obsolete.

Longer limbs and more mass (presumably muscle) could be advantageous in tenpin bowling. The whole arm can be assumed as a fixed rod with a ball held at one end and the shoulder joint as the point of rotation. For an equivalent swing velocity, an increase in the arm length will theoretically lead to an increase in the tangential velocity of the ball (tangential velocity = angular velocity x radius arm). Hence, it is theoretically possible that individuals with longer limbs would have an advantage by having to put in less effort to reach the desired ball release speeds. With modern bowling considered to be a power game, this would mean that the longer 'arm' provided by the longer segments and larger muscle mass would be the desired foundation towards becoming a good bowler. Consequently, talent identification programs in bowling may benefit by paying particular interest to young bowlers with above average build and upper limb length.

Despite several anthropometric differences between the bowlers and non-bowlers, more importantly, there was no significant anthropometric difference specifically distinguishing the elite from the semi-elite bowlers. This finding was also supported by the fact that none of the anthropometric variables showed a significant linear relationship with BS_{ave}. Collectively, it would seem that bowling unlike certain physical based sports (i.e. basketball, volleyball, and rugby), is a sport where participants of all sizes – big or small – have a pretty equal chance of being successful at the highest level.

Meanwhile, in terms of isometric strength measurements, the only notable differences were found for FIR and arm flexion. Furthermore, although not significantly correlated, the highest correlation to BS_{ave} was also for FIR and arm flexion.

For FIR, there appeared to be a significant difference between groups. More specifically, the follow-up test showed that FIR strength was higher for the elite bowlers as compared to the non-bowlers. With forearm/wrist rotators as the most likely primary generators of the tremendous ball spin commonly seen in the modern game and considering that skilful and experienced players impart huge amounts of spin on the bowling ball, the first possibility is that the elite bowlers developed stronger internal rotators of the forearm/wrist region, having amassed much more practice and playing years. A study on handball corroborated this possibility of strength increasing with playing years whereby the authors showed that ball throwing velocity and strength greatly increased with just *one* regular season of active competition (Gorostiaga, 2006). Comparatively, a Malaysian elite bowler participates in various competitions and is in active training for 10 months in a year (Cheah, 2009).

A second possibility is that the physical requirements of the sport contributed to the differences in the FIR between the elite and non-bowling group. A common misconception is that bowling is not a physically challenging sport (Thomas, Schlinker, & Over, 1996; Wiedman, 2006). In reality, a bowler swings a 12 to 16 pound ball, for 12 to 21 times a game for usually six games a day, during competition. Each swing is executed at a considerable speed to generate high ball momentum. It has been argued that a decent amount of muscle strength and muscle endurance was required for the execution of the delivery (Tan, Aziz, & Teh, 2000; Tan et al, 2001). Hence, the participants in the elite group could have possessed a higher degree of FIR strength which was required to be successful .

To answer this quandary, a partial correlation was done looking at the relationship between FIR and BS_{ave} while controlling for years of playing experience. The result was not significant ($r = .36$, $p < .05$), the relationship was only marginally higher than when playing experience was not controlled for. This suggested that elite bowlers had stronger FIR irrespective of how long they had played bowling. However it can be argued that this suggestion is not conclusive, as years of playing experience does not necessarily equate to actual competition and training hours.

Apart from the contributions of the forearm/wrist rotators, significant differences between groups were also detected for arm flexion strength. The follow-up ANOVA revealed that the male elite bowlers were stronger than their non-bowling counterparts. This result appeared logical considering that the arm flexors play an integral role in the forward motion of the forearm in the final phase of the swing. However, the female elite bowlers did not appear to be stronger than the female non-bowlers. There could be two possible explanations for the contrast between genders. Firstly, the females may have employed a different strategy in their swing. Instead of utilising a lot of strength, they relied on optimum technique to achieve the same competitive scores. Female bowlers may have concentrated on spin and accuracy rather than outright ball speed. This explanation is highlighted in a swimming technique study whereby the female swimmers employed a different front crawl technique to achieve the same effective velocity as males (Seifert, Boulesteix, & Chollet, 2004). Alternately, it is also likely that as the strength of bowlers increased over the period of participation, these changes were possibly more apparent in the men possibly due to hormonal differences between genders.

Interestingly, finger pinch strength did not differ between the groups. One would assume that a strong finger grip was needed to have good control of the heavy bowling ball but the results did not support this assumption. It is likely that proper ball grip technique was more important than outright finger strength when it came to handling the ball. This result was in agreement with one study that found that hand grip strength was not correlated with bowling scores (Tan, Aziz, & Teh, 2000). The authors had suggested that there was a strength threshold that was needed to bowl competitively, after which, further strength gains were not essential. This suggestion seem to hold true here as well as the correlation coefficient of all strength variables to BS_{ave} was weak and non significant, leading to an assumption of a threshold. Nonetheless, results from the strength tests provides a useful input for coaches in terms of highlighting the necessary muscle groups that need to be trained to be competitive in bowling.

This study explored the anthropometric and strength parameters that bests distinguished the elite, semi-elite and non-bowlers; with the best discriminators being considered the critical parameters. A number of studies had successfully demonstrated that it was possible to statistically discriminate good and not so good players in various sports (Barker et al., 1993; Barrett & Manning, 2004; Gabbett & Gieorgieff, 2007; Mohamed et al., 2009; Reily, Bangsbo, & Franks, 2000; Tan et al., 2009).

Utilising the discriminant analysis, the generated function successfully classified 54.0% of the participant into their respective groups. In a three group setting such as in this study, there was a 33.33% possibility of placing a group member in the correct group by chance, hence, an overall prediction accuracy that is double the value of chance would have been ideal. For example, in a two group study using discriminant analysis, a prediction accuracy of 87.2% between elite and non-elite handball players was possible (Mohamed et al., 2009). Based on the current results, it can be implied that it was not entirely possible to successfully distinguish ten pin bowling playing ability from the selected physical characteristics used in this study alone. Caution must be applied in interpreting the discriminant function, as there was multicolinearity between the discriminator variables which necessitated the removal of some variables from the analysis. For future research, a different set of non-correlated variables should be used so that more predictor variables could be used in the function and possibly increase its group predicting accuracy.

From the discriminant analysis, the FIR appeared to be the best distinguishing variable. Along with the higher strength scores in the elite compared to non-bowlers group, the relevance of FIR and ball spin in modern bowling was further supported and subsequently, the importance of placing emphasis on strengthening the relevant arm rotator muscles in bowler training are highlighted.

However, in relation to main objective of this study, the poor ability to especially discriminate the semi-elite bowlers (only 16.7% success rate) coupled with the fact that there were no significant differences in any of the anthropometric and strength variables between elite and semi-elite bowlers suggested that there were no outstanding critical parameters for anthropometry and strength based on the selected variables that was tested for.

4.3 **Kinematic Analysis**

4.3.1 **Kinematic Analysis Results**

4.3.1.1 **Movement Patterns**

The near similar patterns of angular displacement and angular velocity for the shoulder, elbow, hip and knee are presented graphically in Figures 4.2 and 4.3.

4.3.1.2 **Kinematic Differences between Groups**

The results are separated into seven sections (i.e., foot slide, knee joint, hip joint, trunk position, shoulder joint, elbow joint, and ball height and ball velocity). Means and standard deviations across all groups and genders for all variables in each section are presented in Tables 4.5, 4.6, 4.7, 4.8, 4.9, 4.10 and 4.12 respectively.

Foot Slide - There was a significant main effect for gender for anterior-posterior velocity at FFS ($F_{1, 26} = 9.55$, $p = .005$), anterior-posterior maximum velocity ($F_{1, 26} = 8.74$, $p = .007$) and anterior-posterior maximum deceleration ($F_{1, 26} = 5.55$, $p = .027$). There were no significant effects for groups. Interaction effects were also undetected.

Knee Joint - Similar to the foot slide, only significant gender effects were found, whereby the angle range ($F_{1, 26} = 7.98$, $p = .009$) for the males were bigger than the female bowlers.

Hip Joint - Although there was a significant interaction effect for hip joint angle at TBS, $F(_{1, 26}) = 5.91$, $p = .022$, no significant group differences were detected in the follow-up test. There was also a significant gender effect for hip joint angle at FFS, $F(_{1, 26}) = 5.51$, $p = .027$ but gender effect was not a priority area for this study.

Trunk Position - Only one significant effect was detected, for gender, for anterior-posterior maximum deceleration, $F(_{1, 26}) = 6.62$, $p = .016$.

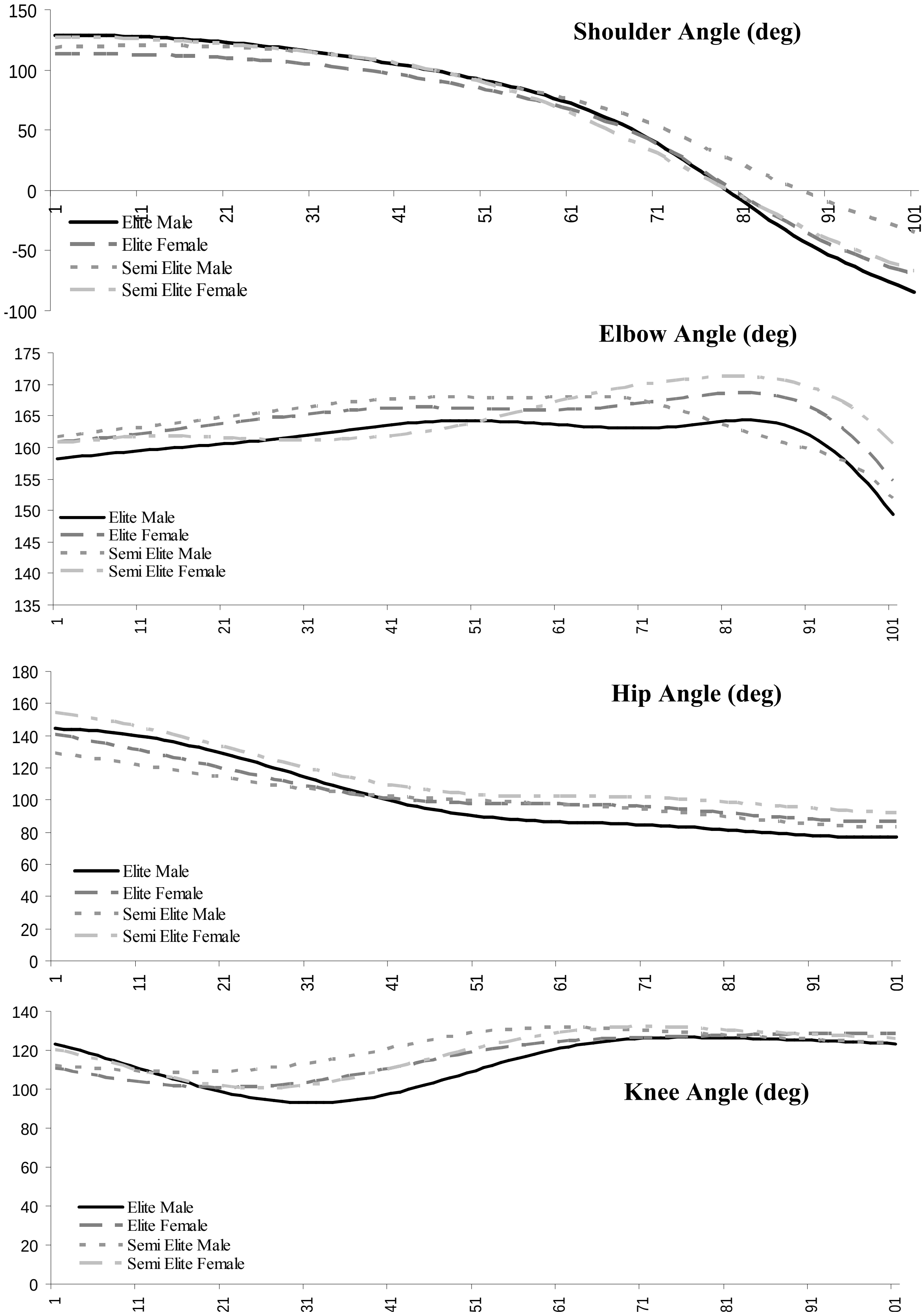


Figure 4.2: Angle-time graph of the shoulder, elbow, hip and knee

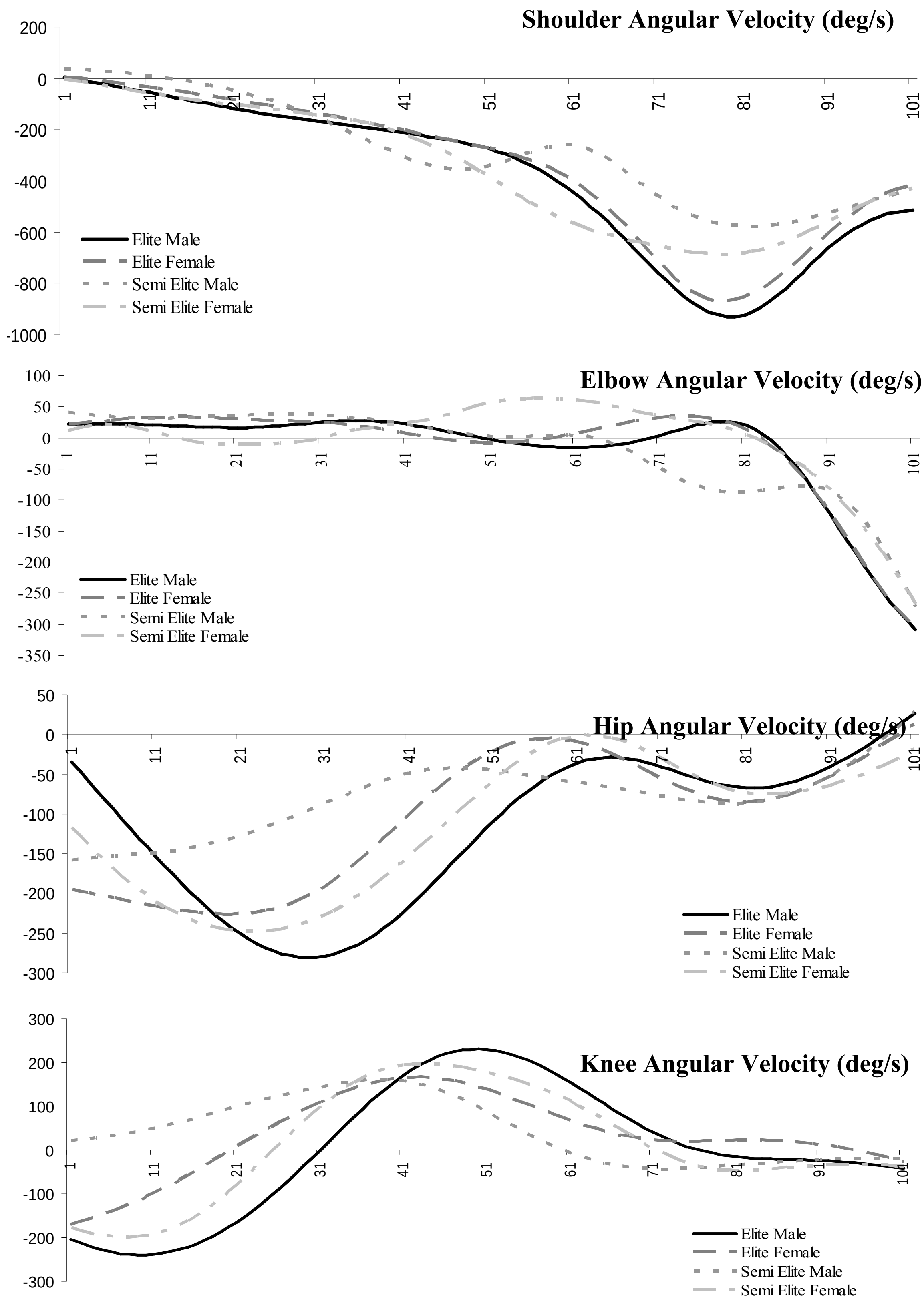


Figure 4.3: Angular velocity-time graph of the shoulder, elbow, hip and knee

Table 4.5: Means for kinematic and inter-trial variability variables of the foot slide (N=29)

Kinematic Variable	Elite	Semi-Elite	Elite (M)	Elite (F)	Semi-Elite (M)	Semi-Elite (F)
Ant-Post Velocity at FFS (m/s) §	6.09 ±0.63	5.99 ±0.71	6.36 ±0.62	5.77 ±0.49	6.36 ±0.61	5.56 ±0.61
Ant-Post Peak Velocity (m/s) §	6.16 ±0.66	6.08 ±0.75	6.42 ±0.66	5.84 ±0.52	6.46 ±0.68	5.62 ±0.61
Time of Ant-Post Peak Velocity (s)	0.19 ±0.07	0.17 ±0.10	0.22 ±0.05	0.15 ±0.07	0.16 ±0.11	0.18 ±0.09
Ant-Post Peak Deceleration (m/s^2) §	-34.34 ±8.98	-35.28 ±10.60	-38.10 ±7.81	-29.64 ±8.49	-38.82 ±12.07	-31.02 ±7.58
Time of Ant-Post Peak Deceleration (s)	0.31 ±0.06	0.30 ±0.10	0.33 ±0.06	0.28 ±0.06	0.28 ±0.13	0.33 ±0.05
Slide Distance (m)	1.04 ±0.15	0.92 ±0.19	1.01 ±0.18	1.09 ±0.10	0.88 ±0.23	0.98 ±0.13
Variability Variable	**Elite**	**Semi-Elite**	**Elite (M)**	**Elite (F)**	**Semi-Elite (M)**	**Semi-Elite (F)**
SD of Lateral Position at FFS ▲*	0.015 ±0.007	0.023 ±0.010	0.017 ±0.005	0.014 ±0.009	0.018 ±0.007	0.030 ±0.010
SD of Lateral Position at REL	0.015 ±0.008	0.019 ±0.007	0.013 ±0.006	0.018 ±0.009	0.021 ±0.006	0.016 ±0.009
SD of Ant-Post Position at FFS	0.151 ±0.071	0.136 ±0.068	0.163 ±0.083	0.137 ±0.055	0.170 ±0.061	0.096 ±0.055
SD of Ant-Post Position at REL	0.023 ±0.018	0.030 ±0.020	0.025 ±0.018	0.022 ±0.020	0.032 ±0.022	0.028 ±0.018
SD of Slide Distance ▲	0.073 ±0.024	0.047 ±0.019	0.062 ±0.022	0.086 ±0.020	0.048 ±0.021	0.046 ±0.019

* Significant interaction effect (p<0.05)
§ Significant main effect for gender, significant difference (p<0.05) between males and females
▲ Significant main effect for group, significant difference (p<0.05) between elite and semi-elite bowlers

Table 4.6: Means for kinematic and inter-trial variability variables of the knee joint (N=30)

Kinematic Variable	Elite	Semi-Elite	Elite (M)	Elite (F)	Semi-Elite (M)	Semi-Elite (F)
Angle at TBS (deg)	117.29 ±18.84	115.40 ±26.02	122.61 ±17.74	110.64 ±19.14	111.94 ±29.39	120.25 ±22.72
Angle at FFS (deg)	98.72 ±8.38	107.81 ±13.93	96.68 ±7.03	101.28 ±9.68	110.57 ±17.64	103.94 ±5.89
Angle at REL (deg)	125.80 ±6.70	124.55 ±12.74	123.90 ±6.59	128.17 ±6.47	123.53 ±16.30	125.99 ±6.59
Angle Range (deg)§	44.68 ±8.80	51.50 ±18.25	48.65 ±9.71	39.70 ±4.00	58.49 ±20.56	41.71 ±8.73
Variability Variable	**Elite**	**Semi-Elite**	**Elite (M)**	**Elite (F)**	**Semi-Elite (M)**	**Semi-Elite (F)**
SD of Angle at TBS	7.28 ±3.80	8.79 ±4.47	7.90 ±4.51	6.49 ±2.74	9.68 ±4.89	7.55 ±3.96
SD of Angle at FFS	3.73 ±1.65	2.70 ±1.52	3.53 ±1.58	3.98 ±1.81	3.14 ±1.72	2.08 ±1.05
SD of Angle at REL	4.64 ±2.47	4.24 ±3.38	4.98 ±2.77	4.21 ±2.14	3.88 ±2.68	4.73 ±4.47
SD of Angle Range §*	6.03 ±2.61	6.58 ±3.17	6.21 ±2.14	5.79 ±3.24	8.44 ±2.13	3.99 ±2.54

* Significant interaction effect (p<0.05)
§ Significant main effect for gender, significant difference (p<0.05) between males and females
▲ Significant main effect for group, significant difference (p<0.05) between elite and semi-elite bowlers

Table 4.7: Means for kinematic and inter-trial variability variables of the hip joint (N=30)

Kinematic Variable	**Elite**	**Semi-Elite**	**Elite (M)**	**Elite (F)**	**Semi-Elite (M)**	**Semi-Elite (F)**
Angle at TBS (deg)*	144.35 ±13.53	139.42 ±24.34	147.30 ±14.48	140.65 ±12.12	129.07 ±24.81	153.91 ±16.01
Angle at FFS (deg)§	104.98 ±13.71	108.16 ±14.66	99.82 ±10.30	111.43 ±15.31	103.24 ±14.03	115.05 ±13.92
Angle at REL (deg)	82.32 ±12.20	86.99 ±8.97	78.90 ±13.10	86.59 ±10.17	83.39 ±7.48	92.02 ±9.11
Angle Range (deg)	74.05 ±12.53	68.96 ±17.17	74.99 ±15.08	72.87 ±9.28	65.69 ±18.11	73.55 ±16.56
Variability Variable	**Elite**	**Semi-Elite**	**Elite (M)**	**Elite (F)**	**Semi-Elite (M)**	**Semi-Elite (F)**
SD of Angle at TBS	5.91 ±3.34	4.92 ±4.78	5.18 ±3.39	6.81 ±3.26	6.01 ±6.07	3.39 ±1.59
SD of Angle at FFS	3.95 ±1.90	2.88 ±1.55	3.44 ±2.07	4.58 ±1.57	2.42 ±1.45	3.52 ±1.60
SD of Angle at REL	4.55 ±2.65	4.65 ±2.39	5.09 ±3.42	3.88 ±1.04	5.04 ±2.20	4.11 ±2.80
SD of Angle Range	4.82 ±4.02	6.84 ±5.10	3.30 ±2.62	6.71 ±4.81	6.83 ±4.72	6.84 ±6.18

* Significant interaction effect (p<0.05)
§ Significant main effect for gender, significant difference (p<0.05) between males and females
▲ Significant main effect for group, significant difference (p<0.05) between elite and semi-elite bowlers

Table 4.8: Means for kinematic and inter-trial variability variables of the trunk (N=30)

Kinematic Variable	Elite	Semi-Elite	Elite (M)	Elite (F)	Semi-Elite (M)	Semi-Elite (F)
Ant-Post Velocity at TBS (m/s)	2.22 ±0.28	2.21 ±0.32	2.26 ±0.32	2.17 ±0.23	2.29 ±0.34	2.09 ±0.27
Ant-Post Velocity at FFS (m/s)	2.67 ±0.36	2.48 ±0.35	2.80 ±0.38	2.50 ±0.26	2.57 ±0.26	2.36 ±0.44
Ant-Post Velocity at REL (m/s)	0.99 ±0.22	0.82 ±0.30	1.02 ±0.23	0.95 ±0.21	0.72 ±0.27	0.96 ±0.32
Ant-Post Peak Velocity (m/s)	2.87 ±0.30	2.69 ±0.28	2.92 ±0.39	2.81 ±0.12	2.74 ±0.18	2.61 ±0.39
Time of Ant-Post Peak Velocity (s)	0.24 ±0.06	0.23 ±0.10	0.24 ±0.08	0.25 ±0.04	0.20 ±0.12	0.27 ±0.03
Ant-Post Peak Deceleration (m/s^2) §	-10.92 ±2.59	-11.11 ±2.61	-11.47 ±3.08	-10.24 ±1.79	-12.53 ±2.17	-9.12 ±1.78
Time of Ant-Post Peak Deceleration (s)	0.43 ±0.06	0.41 ±0.10	0.43 ±0.06	0.42 ±0.05	0.39 ±0.13	0.44 ±0.03
Variability Variable	**Elite**	**Semi-Elite**	**Elite (M)**	**Elite (F)**	**Semi-Elite (M)**	**Semi-Elite (F)**
SD of Lateral Position at TBS *	0.014 ±0.007	0.017 ±0.009	0.015 ±0.009	0.013 ±0.005	0.013 ±0.006	0.023 ±0.008
SD of Lateral Position at FFS	0.013 ±0.007	0.016 ±0.009	0.013 ±0.009	0.013 ±0.005	0.013 ±0.006	0.021 ±0.010
SD of Lateral Position at REL	0.015 ±0.011	0.016 ±0.007	0.015 ±0.014	0.015 ±0.006	0.016 ±0.004	0.016 ±0.011
SD of Ant-Post Position at FFS §	0.059 ±0.026	0.052 ±0.013	0.067 ±0.028	0.048 ±0.021	0.059 ±0.009	0.042 ±0.013
SD of Ant-Post Position at REL	0.021 ±0.011	0.022 ±0.019	0.024 ±0.012	0.017 ±0.006	0.020 ±0.020	0.026 ±0.018
SD of Sup-Infe Position at FFS	0.017 ±0.021	0.009 ±0.004	0.023 ±0.027	0.008 ±0.004	0.011 ±0.003	0.007 ±0.004
SD of Sup-Infe Position at REL	0.012 ±0.016	0.008 ±0.003	0.016 ±0.022	0.008 ±0.002	0.010 ±0.002	0.006 ±0.003

* Significant interaction effect ($p<0.05$)
§ Significant main effect for gender, significant difference ($p<0.05$) between males and females
▲ Significant main effect for group, significant difference ($p<0.05$) between elite and semi-elite bowlers

Table 4.9: Means for kinematic and inter-trial variability variables of the shoulder joint (N=29)

Kinematic Variable	Elite	Semi-Elite	Elite (M)	Elite (F)	Semi-Elite (M)	Semi-Elite (F)
Angle at TBS (deg)	122.99 ±19.41	122.10 ±18.64	131.08 ±18.57	112.87 ±16.17	117.95 ±19.20	127.07 ±18.73
Angle at FFS (deg)	106.16 ±19.10	110.97 ±20.18	106.41 ±19.30	105.84 ±20.17	109.90 ±19.46	112.26 ±23.25
Angle at REL (deg)§	-78.22 ±15.92	-76.98 ±14.85	-84.37 ±15.10	-70.54 ±14.17	-85.22 ±12.59	-67.08 ±11.34
Angular Velocity at FFS (deg/s)▲*	-194.16 ±75.77	-116.62 ±91.19	-217.68 ±61.28	-164.76 ±85.66	-83.29 ±70.77	-156.62 ±104.23
Angular Velocity at REL (deg/s)	-461.64 ±125.44	-438.61 ±95.96	-498.22 ±147.93	-415.92 ±76.03	-443.52 ±124.60	-432.72 ±59.43
Peak Angular Velocity (deg/s)	-1006 ±429.09	-908 ±451.53	-1048 ±372.25	-954 ±513.31	-969 ±590.54	-835 ±249.71
Time of Peak Angular Velocity (s)	75.78 ±4.85	69.73 ±12.65	75.30 ±5.14	76.38 ±4.72	65.17 ±14.27	75.20 ±8.76
Peak Angular Acceleration (deg/s^2)	-10165 ±8109	-10468 ±6984	-10340 ±6765	-9946 ±10039	-14150 ±6973	-6050 ±4054
Time Peak Angular Acceleration (s)	61.17 ±12.39	58.73 ±14.00	64.80 ±6.61	56.63 ±16.55	55.00 ±17.41	63.20 ±8.07
Peak Angular Deceleration (deg/s^2)	7806 ±7300.01	8234 ±6057.22	7452 ±5713.87	8250 ±9330.21	10776 ±6810.35	5184 ±3524.64
Time Peak Angular Deceleration (s)§▲	86.06 ±4.63	79.27 ±12.43	84.20 ±4.59	88.38 ±3.74	73.83 ±12.61	85.80 ±9.47
Angle Range (deg)	201.03 ±32.49	199.07 ±26.44	215.12 ±31.98	183.42 ±24.70	203.17 ±29.17	194.15 ±25.06
TBS to REL Swing Time (s)	0.54 ±0.05	0.53 ±0.10	0.55 ±0.05	0.52 ±0.04	0.52 ±0.13	0.54 ±0.02
Variability Variable	**Elite**	**Semi-Elite**	**Elite (M)**	**Elite (F)**	**Semi-Elite (M)**	**Semi-Elite (F)**
SD of Angle at TBS	2.27 ±1.16	2.43 ±1.12	2.30 ±1.22	2.24 ±1.17	2.45 ±1.35	2.41 ±0.91
SD of Angle at FFS	2.96 ±1.02	3.25 ±2.02	3.29 ±1.01	2.55 ±0.94	2.95 ±2.44	3.61 ±1.57
SD of Angle at REL	5.40 ±3.59	4.30 ±2.06	6.54 ±4.16	4.11 ±2.48	4.34 ±2.22	4.25 ±2.10
SD of Angle Range	6.77 ±5.34	4.18 ±1.71	8.62 ±6.23	4.46 ±2.89	4.53 ±2.24	3.77 ±0.81
SD of TBS to REL Swing Time	0.03 ±0.01	0.03 ±0.01	0.03 ±0.02	0.03 ±0.01	0.03 ±0.02	0.03 ±0.01

* Significant interaction effect ($p<0.05$)
§ Significant main effect for gender, significant difference ($p<0.05$) between males and females
▲ Significant main effect for group, significant difference ($p<0.05$) between elite and semi-elite bowlers

Table 4.10: Means for kinematic and inter-trial variability variables of the elbow joint (N=29)

Kinematic Variable	Elite	Semi-Elite	Elite (M)	Elite (F)	Semi-Elite (M)	Semi-Elite (F)
Angle at TBS (deg)	159.46 ±6.15	160.59 ±6.77	158.36 ±6.25	160.83 ±6.14	160.48 ±6.74	160.73 ±7.60
Angle at FFS (deg)	164.96 ±5.30	163.32 ±8.34	163.77 ±4.83	166.46 ±5.81	165.53 ±5.33	160.22 ±11.31
Angle at REL (deg)§	151.44 ±7.95	155.69 ±7.90	148.72 ±7.59	154.84 ±7.47	152.19 ±7.65	160.60 ±5.69
Angular Velocity at FFS (deg/s)	28.98 ±40.61	7.32 ±52.46	41.27 ±47.88	15.16 ±27.17	13.84 ±57.09	-1.81 ±50.01
Angular Velocity at REL (deg/s) ▲	-325.12 ±83.79	-267.54 ±41.91	-340.34 ±95.98	-306.09 ±66.78	-267.77 ±54.87	-267.22 ±17.71
Angle Range (deg)	8.97 ±7.23	9.33 ±3.78	9.71 ±9.11	8.04 ±4.32	10.71 ±3.77	7.39 ±3.16
Variability Variable	**Elite**	**Semi-Elite**	**Elite (M)**	**Elite (F)**	**Semi-Elite (M)**	**Semi-Elite (F)**
SD of Angle at TBS	2.20 ±1.19	2.72 ±1.81	2.28 ±1.36	2.09 ±1.02	3.04 ±1.74	2.27 ±2.01
SD of Angle at FFS	1.66 ±0.78	2.09 ±1.09	1.82 ±0.70	1.46 ±0.87	2.11 ±0.93	2.06 ±1.40
SD of Angle at REL	4.14 ±4.99	2.59 ±0.87	5.68 ±6.32	2.22 ±1.25	2.34 ±0.90	2.94 ±0.76
SD of Angle Range	3.11 ±1.65	3.63 ±0.83	3.29 ±2.00	2.90 ±1.26	3.65 ±0.62	3.60 ±1.15

* Significant interaction effect ($p<0.05$)
§ Significant main effect for gender, significant difference ($p<0.05$) between males and females
▲ Significant main effect for group, significant difference ($p<0.05$) between elite and semi-elite bowlers

Table 4.11: Means for inter-trial variability variables of the wrist (N=29)

Variability Variable	Elite	Semi-Elite	Elite (M)	Elite (F)	Semi-Elite (M)	Semi-Elite (F)
SD of Lateral Position at TBS *	0.017 ±0.009	0.021 ±0.006	0.021 ±0.010	0.013 ±0.007	0.018 ±0.007	0.024 ±0.005
SD of Lateral Position at FFS ▲	0.014 ±0.009	0.021 ±0.008	0.014 ±0.009	0.015 ±0.009	0.020 ±0.008	0.023 ±0.009
SD of Lateral Position at REL ▲	0.012 ±0.005	0.018 ±0.006	0.011 ±0.004	0.014 ±0.005	0.019 ±0.006	0.016 ±0.008
SD of Ant-Post Position at TBS	0.063 ±0.029	0.061 ±0.017	0.065 ±0.032	0.061 ±0.027	0.068 ±0.017	0.051 ±0.014
SD of Ant-Post Position at FFS	0.044 ±0.021	0.041 ±0.014	0.046 ±0.025	0.041 ±0.017	0.046 ±0.016	0.036 ±0.009
SD of Ant-Post Position at REL	0.044 ±0.031	0.035 ±0.019	0.040 ±0.036	0.048 ±0.026	0.034 ±0.024	0.036 ±0.010
SD of Sup-Infe Position at TBS §	0.019 ±0.010	0.023 ±0.012	0.023 ±0.011	0.014 ±0.006	0.029 ±0.012	0.016 ±0.007
SD of Sup-Infe Position at FFS §	0.055 ±0.032	0.049 ±0.029	0.068 ±0.034	0.039 ±0.019	0.058 ±0.031	0.037 ±0.023
SD of Sup-Infe Position at REL ▲	0.020 ±0.010	0.012 ±0.006	0.021 ±0.010	0.017 ±0.009	0.012 ±0.007	0.013 ±0.004

* Significant interaction effect ($p<0.05$)
§ Significant main effect for gender, significant difference ($p<0.05$) between males and females
▲ Significant main effect for group, significant difference ($p<0.05$) between elite and semi-elite bowlers

Table 4.12: Means for kinematic and inter-trial variability variables of ball height and ball velocity (N=30)

Kinematic Variable	Elite	Semi-Elite	Elite (M)	Elite (F)	Semi-Elite (M)	Semi-Elite (F)
Peak Ball Height (normalised) (m)*	0.945 ±0.105	0.898 ±0.143	0.992 ±0.095	0.887 ±0.090	0.863 ±0.175	0.948 ±0.072
Ball Height (absolute) at REL (m)▲	0.327 ±0.032	0.356 ±0.038	0.329 ±0.031	0.324 ±0.035	0.361 ±0.048	0.348 ±0.017
Variability Variable	**Elite**	**Semi-Elite**	**Elite (M)**	**Elite (F)**	**Semi-Elite (M)**	**Semi-Elite (F)**
SD of Peak Ball Height §	0.020 ±0.011	0.023 ±0.013	0.024 ±0.013	0.015 ±0.006	0.029 ±0.013	0.016 ±0.010
SD of Ball Height (absolute) at REL	0.022 ±0.012	0.016 ±0.007	0.025 ±0.014	0.018 ±0.010	0.019 ±0.008	0.013 ±0.005
SD of Ball Velocity at REL §*	0.250 ±0.190	0.170 ±0.122	0.366 ±0.183	0.105 ±0.044	0.184 ±0.151	0.150 ±0.076

* Significant interaction effect ($p<0.05$)
§ Significant main effect for gender, significant difference ($p<0.05$) between males and females
▲ Significant main effect for group, significant difference ($p<0.05$) between elite and semi-elite bowlers

Shoulder Joint - There were significant effects for gender, group and the interaction between the two. For gender, there were significant differences between the males and females for shoulder joint angle at REL, $F_{(1,\ 26)} = 9.06$, $p = .006$, and for time of maximum angular deceleration, $F_{(1,\ 26)} = 7.64$, $p = .011$. More importantly, for group, there were significant differences between the elite and semi-elite bowlers for angular velocity at FFS, $F_{(1,\ 26)} = 5.59$, $p = .026$, and for time of maximum angular deceleration, $F_{(1,\ 26)} = 4.91$, $p = .036$, with the elite group swinging at a faster rate and decelerating significantly later in the swing, respectively. However, only the correlation between angular velocity at FFS and BS_{ave} was found to be significant ($r = -.438$, $p = .017$). In addition, the interaction for angular velocity at FFS was also significant, $F_{(1,\ 26)} = 4.38$, $p = .047$, and the post hoc test revealed that the shoulder joint of only the male elite bowlers were moving faster than the semi-elite male counterparts.

Elbow Joint - No significant interaction effects were observed. However, there was a significant gender effect for elbow joint angle at REL, $F_{(1,\ 26)} = 6.96$, $p = .014$, and a significant group effect for angular velocity at REL, $F_{(1,\ 26)} = 4.26$, $p = .049$, with the elite group flexing at a higher rate than the semi-elite group. Furthermore, the correlation between angular velocity at REL and BS_{ave} was found to be significant ($r = -.454$, $p = .012$).

Ball Height and Ball Velocity - Although the interaction between gender and group was significant for normalised ball height at TBS, $F_{(1,\ 26)} = 4.90$, $p = .036$, the post hoc test showed that there were no significant group differences within each gender. For absolute ball height at REL, there was a significant group effect ($F_{1, 26} = 4.45$, $p = .045$), with the elite bowlers releasing the ball closer to the lane than the semi-elite bowlers. The correlation between absolute BH at REL and BS_{ave} was also significant ($r = -.43$, $p = .019$)

4.3.2 Discriminant Analysis of Kinematic Variables

Firstly, selection of variables to be included in the discriminant analysis was based on whether there was a significant difference between groups for each variable from the ANOVA results. Subsequently, shoulder velocity at FFS, time of maximum shoulder deceleration, elbow velocity at REL and absolute ball height at REL were shortlisted. Secondly, to adhere to the multicolinearity assumption, short-listed variables that had high co-correlation ($r > .05$) were also omitted. Consequently, time of maximum shoulder deceleration was left out of the analysis. Box's M indicated that the assumptions of equality of variance-covariance matrices were met.

As there were only two groups (elite and semi-elite), the discriminant analysis produced only one function (see Table 4.13). The function was significant ($p = .005$), and the model explains for 39.6% of variation in the grouping variable. The cross-validated classification utilising the function showed that overall, 76.7% of the participants were correctly classified. Within each group, 83.3% of the elite and 66.7% of the semi-elite was correctly placed in their respective groups. There were high ($r > .30$) loadings all variables in the function, with shoulder velocity at FFS being the better discriminator.

Table 4.13: Discriminant function results for kinematic variables

Structure Matrix		Unstandardized Coefficients
Shoulder Velocity at FFS	.59	.01
Absolute Ball Height at REL	.52	17.96
Elbow Velocity at REL	.47	.01
	(Constant)	-2.05

4.3.3 Kinematic Discussion

4.3.3.1 Male and Female Bowlers

Although not the primary objective of this study, it is worth to note that there was significant measurable difference between gender in seven discrete kinematics variables as well as five absolute variability measures. As the BS_{ave} of male and female bowlers were not significantly different, it can be established that the bowlers clearly adopted different ways to achieve the same outcome goals. These differences of pattern between genders were also reported by Chu, Zhang, and Mau (2002) in their exploratory work on ten pin bowling as well as in other sports such as javelin (Gregor, Whiting, & McCoy, 1985); and discus (Leigh & Yu, 2007). In Leigh and Yu's (2007) study, although there was variation in overall throwing performance between male and females, they suggested that elite female discus throwers were reliant on effective technique to achieve long distances, whereas male discus throwers have a relatively homogeneous technique, with a dependence on physical strength to achieve their long throws. This observation could be applicable for bowling considering that the male bowlers in this study were significantly stronger than their female counterparts in nearly all measured areas (see Table 4.2). Even though there are differences in technique and execution consistency between genders, this particular study was primarily interested in the parameters of good performance only. Therefore considering that the male and female bowlers have near similar outcome performance (similar BS_{ave}), there is limited further discussion. Future research could focus specifically gender differences aspect.

4.3.3.2 Kinematic Patterns

Descriptively, the kinematic patterns of both the elite and semi-elite bowlers were graphically similar as presented by the graphs in Figures 4.2 and 4.3. It is very likely that the pattern similarities were due to both groups being relatively high level bowlers (mean BS_{ave}

of 213 and 181 pin falls respectively). A visually distinguishable difference was in the elbow region, and this was probably a consequence of the slight variations in the 'hook' technique between the bowlers. However, this is not able to be proved due to the limitation of the study, as there was a lack of a local reference frame in the elbow region to measure longitudinal arm rotation. On the other hand, future studies utilising a full range from elite to recreational bowlers would likely yield a more varied pattern for most of the variables. For example, Wagner and colleagues (2010) in a study of handball jump throw kinematics of elite and low level players found the that the respective patterns were dissimilar.

4.3.3.3 Critical Kinematic Parameters of the Delivery

The objective of this study was to look at parameters that bests distinguished between playing levels. In this regard, the discriminant analysis highlighted that faster shoulder rotation at FFS was one of the better discriminators. Though, the shoulder velocity was more similar at the later stages of the swing with the ANOVA showing that the groups were not different in terms of shoulder rotation velocity and shoulder angle at release. This suggested that the elite bowler's earlier gain in arm angular velocity from the mid point of the swing (i.e. FFS) could help in giving allowance for compensatory adjustment near release, resulting in a more similar velocity at the end. This is supported by the fact that the elite bowlers also had their peak shoulder deceleration significantly later. It is possible that their better motor ability allowed a much later adjustment in velocity.

A higher elbow flexion velocity at release was another variable that could distinguish the bowlers. This result corresponds with the stronger arm flexion and FIR strength exhibited by the elite bowlers discussed earlier in 4.2.2.The likely cause could be the effort of trying to impart maximum ball spin near release which necessitates quick flexion and internal arm rotation (Strickland, 1996; Wiedman, 2006). It is common for coaching books to associate more ball spin with higher level bowlers, and this was recently supported by Fuss (2009) in his pilot work with an instrumented bowling ball. Hence, the elite bowler's effort to impart more spin would inadvertently result in higher elbow flexion velocity that was found.

Probably the most compelling kinematic discriminator was the ball release height. The elite bowlers released the ball significantly closer to the bowling lane. This is in line with the common coaching instruction of not 'throwing the ball' (Cheah, 2009; Wiedman, 2006). Unskilled bowlers are frequently distinguished by the excessive 'thud' that is heard by them 'throwing' the ball. Energy losses incurred by the ball drop also does not augur well for good pin to pin interaction as the ball would have lost some of its energy that otherwise would have been able to be transferred to the pins. Additionally, the significant, positive correlation coefficient indicated that the closer to the lane the ball was at release, the higher the BS_{ave}. Having said this, it is more than likely that there is a threshold height. Trying to go too low to release the ball will increase the risk of the ball hitting the lane before the actual release, which may cause a bowler to compensate by reducing the approach speed. The finding also has unprecedented applied implications, as there is no known scientific endeavour to actually prove that better bowlers released the ball closer to the lane. Considering that it is easily applicable to routine training, coaches can now instruct new bowlers to explicitly release closer to the ground, somewhere in the region of 30 to 35 cm, which is the mean value of elite bowlers in this study (see Figure 4.4).

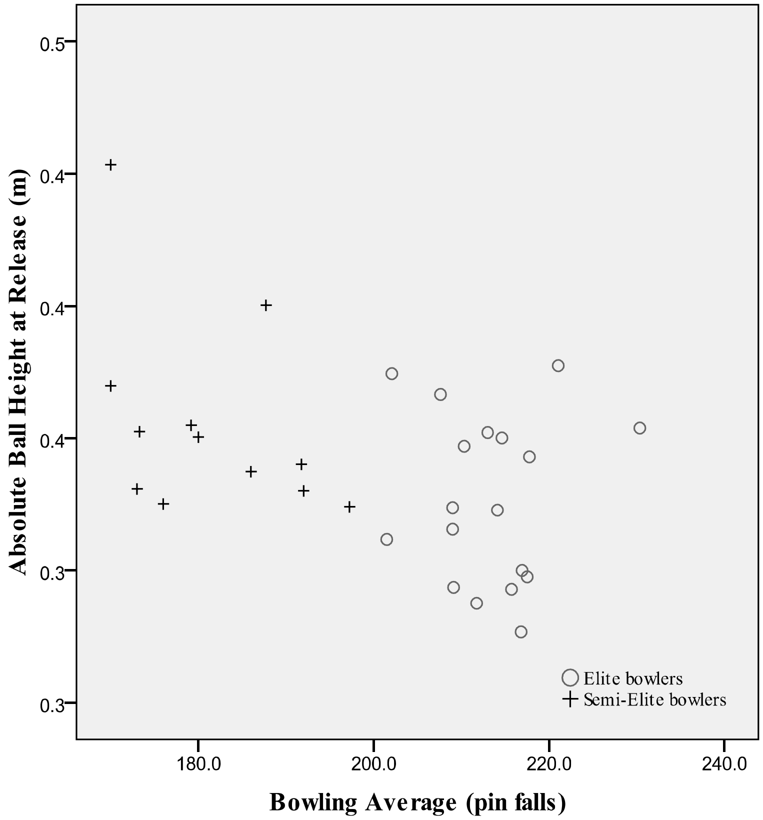


Figure 4.4:Scatter plot of release ball height for various bowling averages

The three kinematic variables discussed above are considered critical parameters of the delivery in ten pin bowling as shown by the discriminant analysis results (Table 4.13). Shoulder velocity at FFS was the variable that best distinguish between elite and semi-elite bowlers, and this was followed by absolute ball height at REL and elbow velocity at REL, respectively. If a coach were to try to predict the probability of a bowler joining the elite ranks solely based on these three variables, he or she would have a more than ¾ respectable chance of getting it right. As these three kinematics variables appear to somewhat define an excellent bowler, future bowling technique research should not fail to include them.

It was interesting to note that the results were devoid of any linear and angular velocity group differences near ball release and neither was there a difference in angle amplitude (range of motion) of the various joints. On the surface, it is in contrast to the beliefs propagated by bowling experts that modern bowling is power dependant (Benson, 2000; Strickland, 1996; Wiedman, 2006). In reality, as the two groups in this study were both highly skilled group of bowlers, the speed related difference (if any) were rather expectedly insignificant. It is more than likely that the bowling experts were qualitatively comparing the modern bowlers with bowling techniques of old, rather than referring to a distinct correlation between ball speeds and bowling score. From the results of this study, it can be safely said that high level bowlers should strive for an end product ball velocity in the vicinity of 8.0 m/s (±0.42 m/s). Anything faster not necessarily equates to better scores and anything slower would more likely be an indication of less than ideal delivery technique.

4.4 <u>Within-Subject Inter Trial Movement Variability</u>

4.4.1 <u>Results of Variability Differences between Group</u>

The variability results have an additional section as compared to the kinematic results and are separated into eight sections (i.e., foot slide, knee joint, hip joint, trunk position, shoulder joint, elbow joint, wrist position, ball height and ball velocity). Means and standard deviations across all groups and genders for all variables in each section are presented in Tables 4.5, 4.6, 4.7, 4.8, 4.9, 4.10, 4.11 and 4.12, respectively.

Foot Slide - There was a significant main effect for group for SD of lateral foot position at FFS ($F_{1, 26} = 9.23$, $p = .006$) and SD of slide distance ($F_{1, 26} = 11.65$, $p = .002$). The elite bowlers were more consistent than the semi-elite bowlers for the SD of Lateral Foot Position at FFS but less consistent for SD of slide distance. More specifically, the Interaction for SD of lateral foot position at FFS was also significant ($F_{1, 26} = 7.25$, $p = .012$), with the follow-up test revealing that the elite females were significantly more consistent than the semi-elite females (U_{13} = 4.00, Z = -2.35, p = .019). For the relationship with average bowling score, a significant correlation was found only for the SD of lateral foot position (r = -.43, p = .022) and slide distance (r = .57, p = .001). There were no significant gender effects.

Knee Joint - For SD of the angle range, there was a significant interaction ($F_{1, 26}$ =4.41, p = .046) and gender ($F_{1, 26}$ =6.46, p = .017) effect. The post hoc analysis revealed that there were no significant differences between the groups with different playing levels.

Hip Joint - No significant effects were observed for the any of the variables.

Trunk Position - A significant gender effect was found for SD of anterior-posterior position at FFS ($F_{1, 26}$ =5.36, p = .029). In addition, a significant interaction effect was also found for SD of the lateral trunk position at TBS ($F_{1, 26}$ =4.33, p = .047), with the follow up test for this significant interaction revealing that the female elite bowlers were more consistent laterally at TBS than the female semi-elite bowlers (U_{13} = 6.00, Z = -2.05, p = .040).

Shoulder Joint - There were no significant effects for the any of the variables.

Elbow Joint - As with the shoulder joint, no significant effects were detected for all.

Wrist Position - There were significant effects for gender, group and the interaction between the two. For gender, there were significant differences between the males and females for SD of superior-inferior wrist position at TBS ($F_{1, 26}$ = 8.26, p = .008), and at FFS ($F_{1, 26}$ = 5.42, p = .028), respectively. For group, there were significant differences for SD of lateral wrist position at FFS ($F_{1, 26}$ = 4.51, p = .043), and at REL ($F_{1, 26}$ = 5.72, p = .024), as well as for SD of superior-inferior position at REL ($F_{1, 26}$ = 4.78, p = .038), with the elite group more consistent at the lateral positions and less consistent at the superior-inferior position compared to the semi-elite group. More specifically, for SD of lateral wrist position at TBS, the interaction was significant, $F_{(1, 26)} = 5.91$, $p = .022$, and the post hoc test revealed that the female elite bowlers were more consistent than the female semi-elite bowlers ($U_{13} = 4.00$, $Z = -2.34$, $p = .019$). Furthermore, where playing level was significant, significant correlations were also found between average bowling score and SD of lateral wrist position at FFS ($r = -.50$, $p = .005$) and at REL ($r = -.41$, $p = .026$), as well as for SD of superior-inferior wrist position at REL ($r = .436$, $p = .016$), respectively.

Ball Height and Ball Velocity - For SD of ball velocity at REL, there was a significant interaction effect ($F_{1, 26} = 4.95$, $p = .035$). The post hoc test revealed that the male elite bowlers had more inconsistent ball velocity scores compared to the male semi-elite bowlers ($U_{17} = 13.00$, $Z = -2.15$, $p = .032$).

4.4.2 Discriminant Analysis of Variability Variables

As mentioned earlier, selection of variables to be included in the discriminant analysis was based firstly on whether there were significant differences between groups for each variable from the ANOVA results. Subsequently, SD of foot lateral position at FFS, SD of foot slide distance, SD of trunk lateral position at TBS, SD of wrist lateral position at TBS, SD of wrist lateral position at REL, and SD of wrist superior-inferior position at REL were shortlisted. Secondly, to adhere to the multicolinearity assumption, shortlisted variables that had high co-correlation ($r > .05$) were omitted.

Consequently, only SD of foot lateral position at FFS, SD of foot slide distance, SD of wrist lateral position at REL and SD of wrist superior-inferior position at REL were used as discriminating variables in the analysis. Box's M indicated that the assumptions of equality of variance-covariance matrices were met.

Again, as there were only two groups (elite and semi-elite), the discriminant analysis produced only one function (see Table 4.14). The function was significant (p = .001), and the model explains for 52.1% of variation in the grouping variable. The cross-validated classification utilising the function suggested that overall, 76.7% of the participants were correctly classified. Within each group, 77.8% of the elite and 75.0% of the semi-elite was correctly placed in their respective groups. There were high (r > .30) loadings for all the variables in the function, with SD of foot lateral position at FFS being the best discriminator.

Table 4.14: Discriminant function results for variability variables

Structure Matrix		Unstandardised Coefficients
SD of Foot Lateral Position at FFS	.56	-45.01
SD of Foot Slide Distance	-.46	29.20
SD of Wrist Lateral Position at REL	-.41	-112.13
SD of Wrist Superior-Inferior Position at REL	. 37	66.68
	(Constant)	-.55

4.4.3 <u>Variability Discussion</u>

In closed skill sports it is often that the outcome is either determined by the best single value of a series of trials (e.g. the javelin) or; by the accuracy towards a target (e.g. archery). In the case for accuracy, higher scores are awarded for attempts that finish nearer a specific location (e.g. 1-3 pin pocket in bowling). These movements are characterised by sub-maximal effort, and outcome is often dependent on the sum of performances over a series of attempts (Miller, 2008). Thus, the ability to generate the same (accurate) outcome consistently is important.

More consistent lateral positioning of the trunk and the slide foot were key discriminators between bowling groups. This finding were in direct relation to the movement consistency needed in bowling and was expected considering the high precision and accuracy requirement to hit pins 1 and 3. Higgins and Spaeth (1972) proposed that a successful movement pattern should be developed and reproduced on each trial to maximise accuracy. This indicated that accurate movement patterns would be characterised by high inter-trial reproducibility. Furthermore, it may be inferred that deviation from a successful movement pattern would be a cause of inaccuracy.

In this study, the lateral positioning of the foot and wrist that were highly reproducible were indicative of higher level bowlers, but because the elite bowlers were not anymore consistent in other areas it would be inaccurate to generalise Higgins and Spaeth (1972) suggestions to the whole delivery motion. Moreover, no evidence was found to suggest that any of the bowlers were able to reproduce the *exact* movement from each delivery, as variability was present at all discrete points (within the limits of experimental error).

On the opposite end of the variability spectrum, motor control experts summed that considering the degree of freedom of the sensorimotor system, "it seems impossible for a given individual to generate identical movement patterns on successive attempts at performing the same task" (Newell & Corcos, 1993). In relation to this, the results showed that the elite bowlers had higher variability in terms of foot slide distance and vertical wrist position at release; both of which were also significant discriminators of playing level. In 2008, Barlett suggested that certain types of movement variability could be attributed to compensatory mechanism employed by skilled athletes. Button et al., (2003) and Robbins et al., (2003) suggested that the compensatory mechanism was present in basketball shooting, which is another accuracy based, sub-maximal skill.

The compensatory suggestion is also plausible for bowling, considering that variations in slide distance could accommodate variations in approach speeds. Bowlers either take four or five steps during approach, in which time it would be extremely difficult to maintain the exact gait velocity and stride length. Coming up short in the last step would necessitate a longer slide to reach closer to the foul line, and vice versa.

The same explanation can also be applied to the arm swing, as the ball push-away and back swing also starts from the very first step of approach. Inadvertently, it is near impossible to acquire the exact same trajectory throughout the swing. Elite bowlers had more variations between trials in wrist height at release (the most distal segment), which possibly permitted final corrections so that the ball was released at the bowler's desired height. This meant that the elite bowlers could have variations in their kinematics, yet still have similar release height as evident by the lack of difference in SD of ball release height between the groups.

From a theoretical perspective, the closed-loop theory of motor control presented by Adams (1971) contends that a performer uses feedback from the early stages of the movement to make adjustments in the latter stages. Thus, slight changes in initial joint actions (i.e. ankle, knee, hips and trunk) that are beyond tolerable system parameters would be counterbalanced by subsequent more distal joint actions. Robbins and colleagues (2006) believed that the increased variability in the elbow and wrist region in basketball shooting was due specifically to this compensatory mechanism. Since the wrist is the last element in the kinematic chain, it is possible that the higher observed values in intra-individual variability represent this motor control mechanism at work in the elite bowlers.

In summary, it appears that the variability results were two fold. On one hand, consistent lateral positioning of the base and most distal segment was highly desirable in line with the needs to maximise accuracy. However this alone did not paint the whole picture for the delivery. Better bowlers also had more variable foot slide distances and hand height at ball release, both of which were the last stages of the delivery motion. This suggested the closed loop motor control mechanism at work, by making final adjustments which compensates for kinematic differences of the earlier stages.

The four absolute variability variables discussed above are considered critical parameters of the delivery in ten pin bowling as shown by the discriminant analysis results (Table 4.15). SD of foot lateral position at FFS was the variable that best distinguished between elite and semi-elite bowlers, and this was followed by SD of foot slide distance, SD of wrist lateral position at REL and SD of wrist superior-inferior position at REL respectively. If one were to try to foretell whether a bowler was cut out for the elite ranks solely based on these four variables, they would have a 76.7 percent chance of getting it right. As it stands, future bowling technique research should endeavour to include all four of these consistency variables, as it defines a good bowler from an excellent one.

4.5 Segment Contribution

4.5.1 Results

There were no significant differences in terms of the various segment contributions to the final ball velocity at release between the elite and semi-elite groups (Table 4.15). The contributions were also similar for both genders. Segment linear velocity-time graphs are presented in Figure 4.5 and 4.6. It shows a similar pattern of sequentiallity, with the peak of the distal segments occurring following the deceleration of the preceding proximal segment.

4.5.2 Contribution and Sequence towards Ball Release Velocity

It has been established that sequential increase in velocities from proximal to more distal segments are evident in throwing for maximal distance/speed (Atwater, 1979) and in some events with high accuracy requirements (Hayes, 1988). The results of the segment endpoint linear velocities (see Figures 4.5 and 4.6) clearly suggested that the ball delivery in ten pin bowling was sequential in nature as opposed to being simultaneous. This result was the first of its kind documented for ten pin bowling, a sport which has a speed-accuracy trade-off emphasis. Such observations were common in movements with maximal velocity priority, including those of another underarm pattern, the softball windmill pitch. Alexander and Haddow (1982) was first to report that there were sequential decelerations occurring in the proximal segments prior to release of the softball, and this was supported in a more recent study by Oliver, Dwelly, and Kwon (2010).

In this present study there were no significant differences between the groups in terms of how much each segment contributed towards the final ball velocity (Table 4.15). In contrast, Oliver, Dwelly, and Kwon (2010) had presented the arm segment contributions in intermediate and advanced softball pitchers, with the former relying more on the upper arm and forearm. The difference in findings was most likely a consequence of the objective of ten pin bowling, which was not solely about ball speed. Should all the bowlers try to achieve maximal ball velocities, one would assume that there would be a difference in segment contributions between playing level; for example the elite level bowler might walk faster during approach compared to a semi-elite bowler.

Table 4.15: Means for percentage (%) of segment contributions towards final ball velocity (N=30)

Segment	Elite	Semi-Elite	Elite (M)	Elite (F)	Semi-Elite (M)	Semi-Elite (F)
Lower Body (walking speed) - Hip marker	37.87 ±3.92	36.95 ±3.90	36.69 ±4.32	39.33 ±2.97	36.47 ±3.01	37.62 ±5.22
Trunk (flexion + rotation) - Shoulder marker	0.50 ±4.61	3.32 ±4.44	1.24 ±4.45	-0.43 ±4.94	5.38 ±3.92	0.44 ±3.66
Upper arm (underarm swing) - Elbow marker	18.90 ±6.33	17.02 ±4.84	21.37 ±6.61	15.82 ±4.64	16.80 ±5.69	17.32 ±3.95
Lower arm (flexion) - Wrist marker	29.10 ±4.23	28.11 ±5.52	29.96 ±5.10	28.02 ±2.76	28.75 ±6.62	27.21 ±4.04
Wrist (flexion) - Metacarpal marker	12.45 ±3.88	11.76 ±4.14	12.20 ±4.39	12.76 ±3.41	9.51 ±4.01	14.90 ±1.41
Fingers - ball velocity increment after wrist	1.19 ±5.03	2.86 ±6.72	-1.46 ±3.91	4.50 ±4.40	3.10 ±7.44	2.52 ±6.38

* Significant interaction effect (p<0.05)
§ Significant main effect for gender, significant difference (p<0.05) between males and females
▲ Significant main effect for group, significant difference (p<0.05) between elite and semi-elite bowlers

Table 4.16: Normalised torques at the shoulder, elbow and wrist joints.

Joint torques (%BW*H)	Elite	Semi-Elite	Elite (M)	Elite (F)	Semi-Elite (M)	Semi-Elite (F)
Peak shoulder flexion	9.62 ±4.95	11.04 ±5.28	10.93 ±2.90	8.08 ±6.60	14.22 ±7.34	7.86 ±1.80
Peak shoulder extension(-)	4.24 ±4.90	6.86 ±5.64	4.74 ±3.01	3.66 ±6.79	8.97 ±6.94	4.76 ±3.76
Peak elbow flexion	2.65 ±1.54	3.10 ±2.24	2.95 ±1.52	2.31 ±1.61	4.95 ±1.54	1.25 ±0.51
Peak elbow extension(-)	3.70 ±1.99	4.73 ±2.18	3.72 ±1.87	3.67 ±2.30	5.80 ±2.67	3.67 ±0.72
Peak wrist flexion	1.71 ±0.85	1.63 ±0.49	1.88 ±0.55	1.52 ±1.14	1.55 ±0.49	1.70 ±0.56
Peak wrist extension(-)	0.92 ±1.12	0.89 ±0.50	0.88 ±0.57	0.97 ±1.62	0.98 ±0.41	0.81 ±0.62

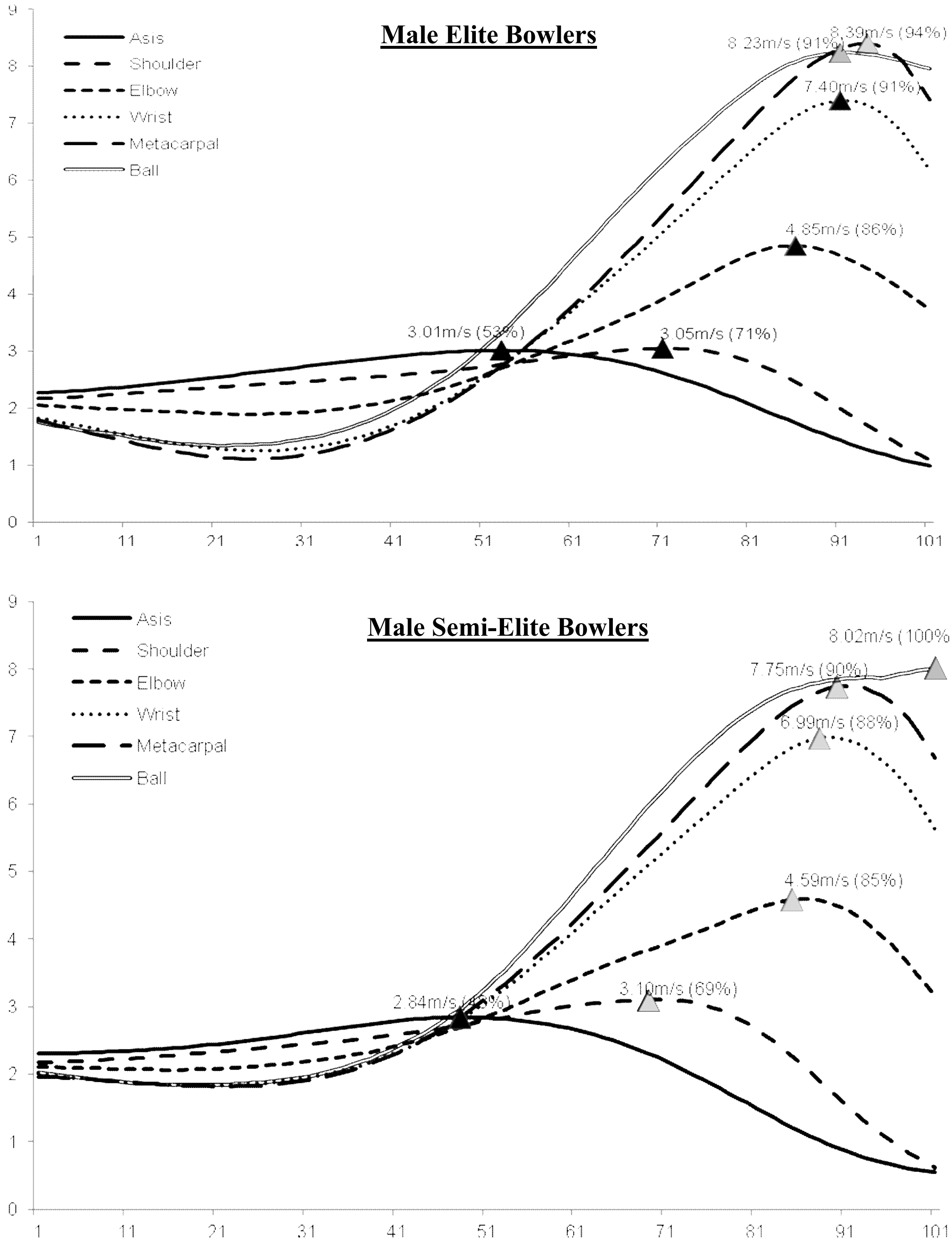
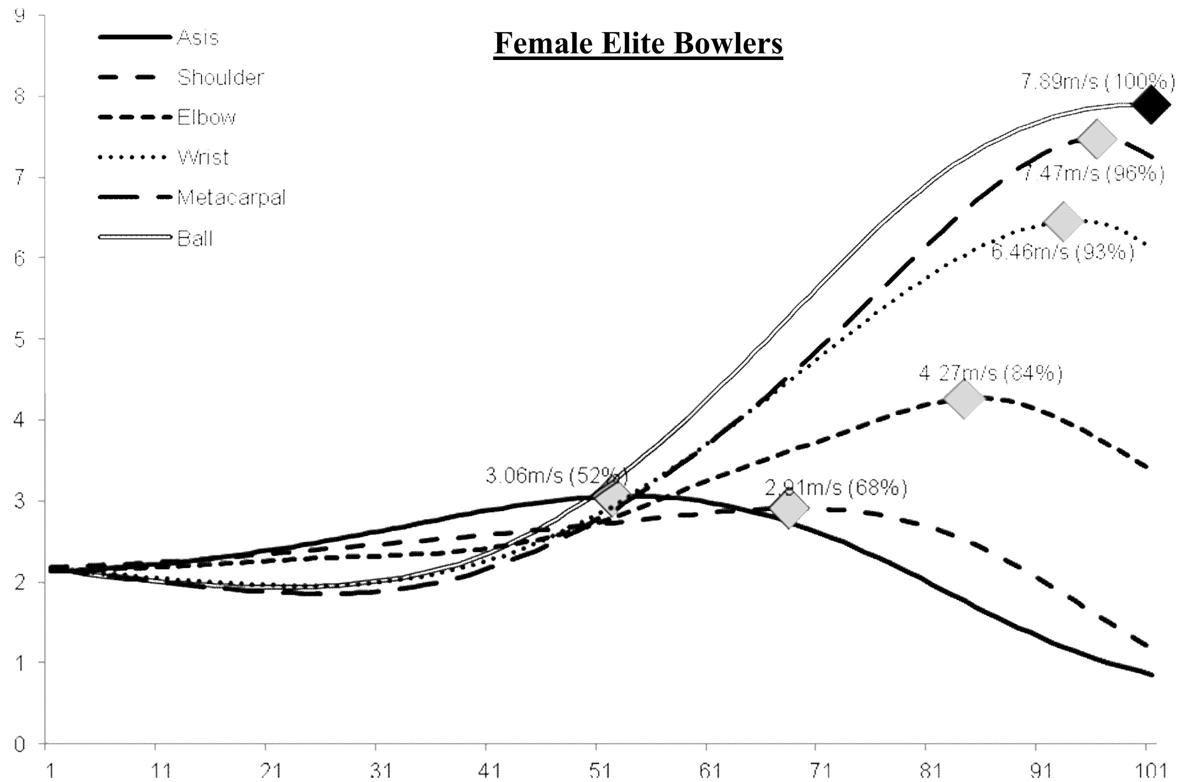


Figure 4.5: Sequence of peak linear velocities (m/s) of segments for male bowlers



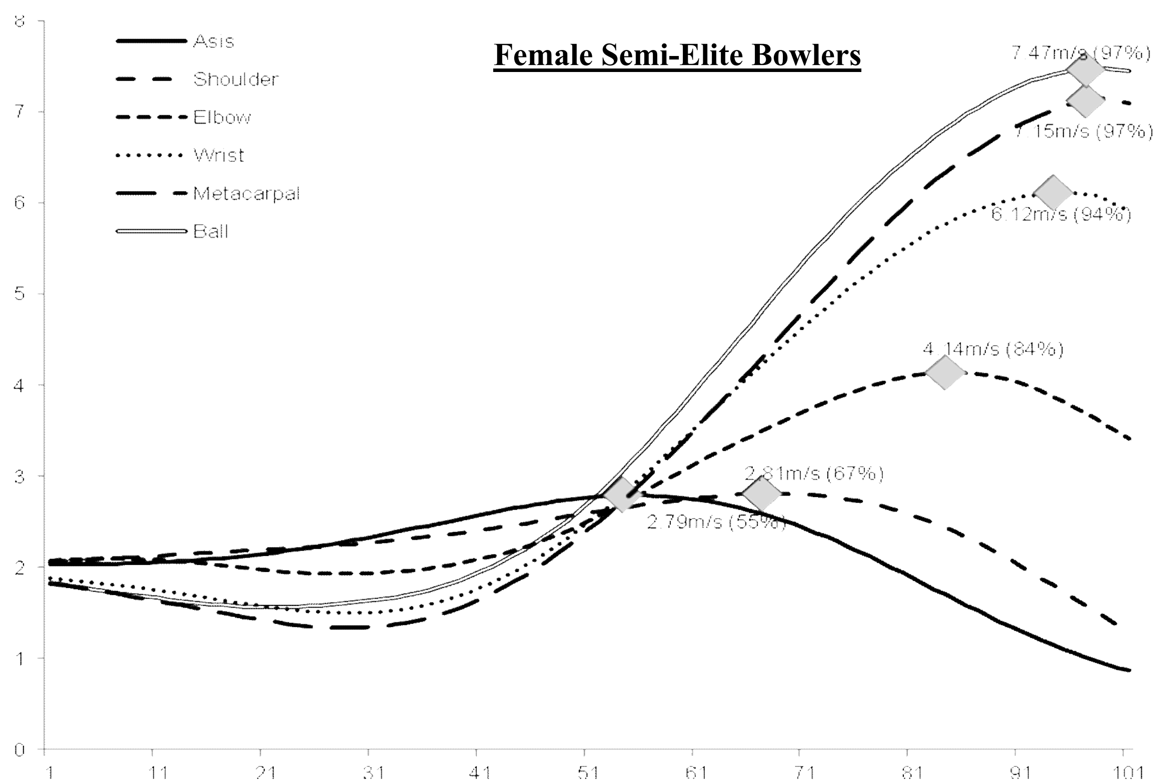


Figure 4.6: Sequence of peak linear velocities (m/s) of segments for female bowlers

Considering that the contributions are near similar for both groups, it can be summed in total that the final linear ball velocity in ten pin bowling (average of 8 m/s) stemmed from contributions of the lower limb during approach (37.4%), rotation and flexion of the trunk (1.6%), upper arm (18.1%), lower arm (28.7%), with the wrist and fingers contributing (13.9%).This meant that the upper limbs had a combined contribution of 60.7%, while the trunk had the least contribution. Sidearm throws (Van den Tillaar & Ettema, 2004b) and overarm throws (Gordon & Dapena, 2006) also displayed these similar characteristics.

The results presented the contribution of individual segments in attaining the ball release velocity. In applied terms, coaches and bowlers would be able to make necessary adjustments for certain shortcomings. For example, a shorter bowler with lower ball height reach (lower potential energy) should compensate by walking faster during approach to attain the desired ball release velocity.

However, caution must be used in interpreting the results, as unlike other movements, bowling involves a very heavy ball and the underarm pattern allows for a preparatory phase for the ball to be lifted at heights, allowing it to freefall. Arm swing in ten pin bowling is suggested to be gravity driven (Benson, 2000), compared to the internal arm rotation of baseball pitching (Van den Tillaar & Ettema, 2004a) and the underarm swing of softball pitching (Werner et al., 2006) which involves high muscle torque. In relation to this, firstly it would be of interest to further investigate whether bowlers were *actively* trying to accelerate their arms during swing or left it to freefall. Secondly, considering the elbow and wrist joints are attached about the upper arm segment at the shoulder – measuring horizontal linear velocities alone might not best represent the respective individual upper limb contribution. To help answer these quandaries, the following supplementary analysis was conducted.

4.5.2 Estimation of Upper Limb Joint Torques

Through inverse dynamics it was possible to estimate torques about the shoulder, elbow and wrist during delivery utilising the kinematic and anthropometric data collected. A simple planar (2D) model was used. The mathematical model for a three-link kinematic chain of an arm was constructed based on Kane's vector-based approach method. The original model was first presented by Ariff and Rambely (2009) and was used to study the smash motion in badminton. The detailed computational methods for the model are available in Appendix 5. It had a racket forming the end segment together with the hand and an external force in the form of the shuttle contacting the racket. The model was adapted for use in bowling motion by removing the external contact force and, as the bowling ball was cupped, it was considered to form the final segment together with the hand. Computations were done using the R software package (R Development Core Team, 2003). To remove the effects of body size in comparisons, joint torques were reported as values normalised to the product of the participant's body weight and height.

Important assumptions for this model are that:

- the segments have a fixed mass represented by the point of centre of mass (COM).
- the position of the segments COM are fixed throughout the motion.
- the length of the segments are constant throughout the motion.
- the joints are considered as frictionless hinge joints.
- the bowling ball is a solid sphere with uniformly distributed mass.
- the arm swing motion is entirely in a single plane.

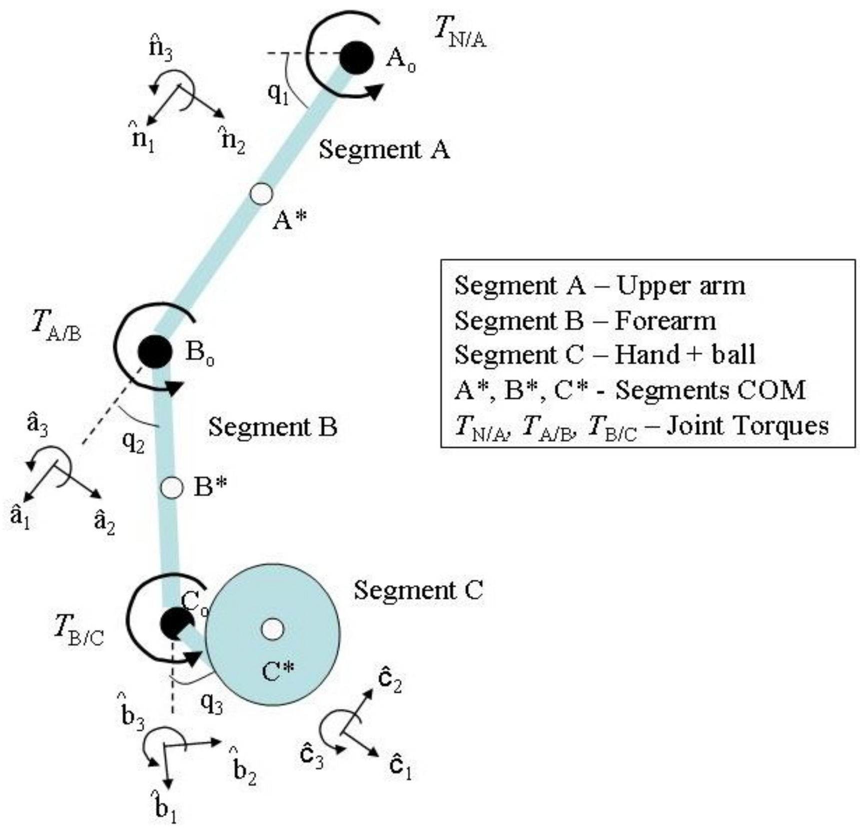


Figure 4.7: Model of a planar three-link kinematic chain of the arm

Figure 4.7 presents a planar kinematic chain of the arm with three degrees of freedom, represented by the angles q_1, q_2 and q_3. Segment A is connected to the reference frame N by the frictionless A_o joint. Segment B is connected to segment A by the frictionless joint B_o; and segment C is connected to segment B by the frictionless joint C_o. While n_i, $\hat{a}_i$, b_i, $\hat{c}_i$, (i= 1, 2, 3) are mutually orthogonal unit vectors that determines the direction of the vector component for the segments A, B, C and the reference frame N.

To compute torques about the shoulder, elbow and wrist, the following individual body parameters of the bowlers needed to be generated:

i. Segment lengths taken from anthropometric measurements (see section 3.1.1)

ℓ_A = measured length of the upper arm

ℓ_B = measured length of the forearm

ℓ_C = estimated hand thickness and diameter of bowling ball = (0.02 + 0.218) m

ii. Distance of COM of segment to its proximal end. Estimates of COM percentage location are based on tables provided in Winter (2005) (see also Appendix 4).

ρ_A = COM distance for segment A = ℓ_A × (estimate percentage of A^*)

ρ_B = COM distance for segment B = ℓ_B × (estimate percentage of B^*)

ρ_C = hand thickness and COM location of ball = (0.02 + 0.109) m

iii. Mass of segments was estimated from pre-determined percentage of body mass as provided by Winter (2005).

m_A = mass of upper arm = (participants body mass × 0.028) kg

m_B = mass of forearm = (participants body mass × 0.016) kg

m_C = mass of hand and ball = (participants body mass × 0.006) kg + (mass of ball)

iv. Moment of inertia about the COM of segments A,B and C. Radii of gyration values for upper arm and forearm are provided by Winter (2005). Moment of inertia of the hand + ball segment is calculated directly by assuming it is one solid uniform sphere.

$I_{A*} = [(m_A \times 0.542^2) + (m_A \times \rho_A^2)]$ kgm^2

$I_{B*} = [(m_B \times 0.526^2) + (m_B \times \rho_B^2)]$ kgm^2

$I_{C*} = [(2/5)(m_C \text{ x } 0.109^2)]$ kgm^2

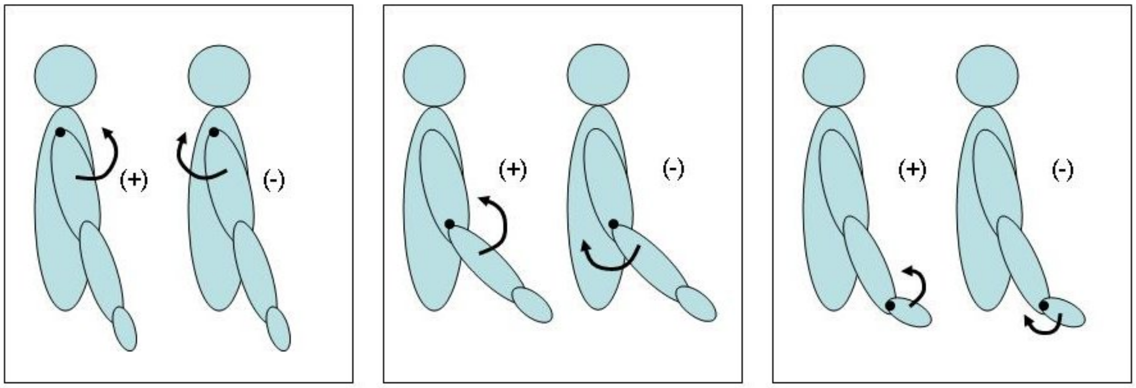


Figure 4.8: Convention for sagittal plane flexion (+) and extension (-)

Peak normalised torques of the shoulder, elbow and wrist are presented in Table 4.16. Visual representation of the respective torque curves are presented in Figure 4.9. Two- way analysis of variance for playing level and gender yielded no significant differences between the elite and semi-elite bowlers or between gender in terms of peak torque generated at the shoulder, elbow or wrist.

Discussion

All bowlers displayed higher torque values at the shoulder, followed by the elbow and wrist, and this corresponds with the proximal to distal segment contributions and sequence discussed in the earlier section. It is now evident by the torques generated at the three joints that the shoulder region contributed the most to ball velocity as compared to other upper limb segments.

Interestingly, the torques at each of the joints displayed rather gradual slope from TBS right up to around 70% of the delivery cycle (Figure 4.9). From then on, the shoulder joint exhibited a sharp decrease in flexion torque followed by an increase in extension torques prior to ball release. This seemingly 'braking' component could possibly be an

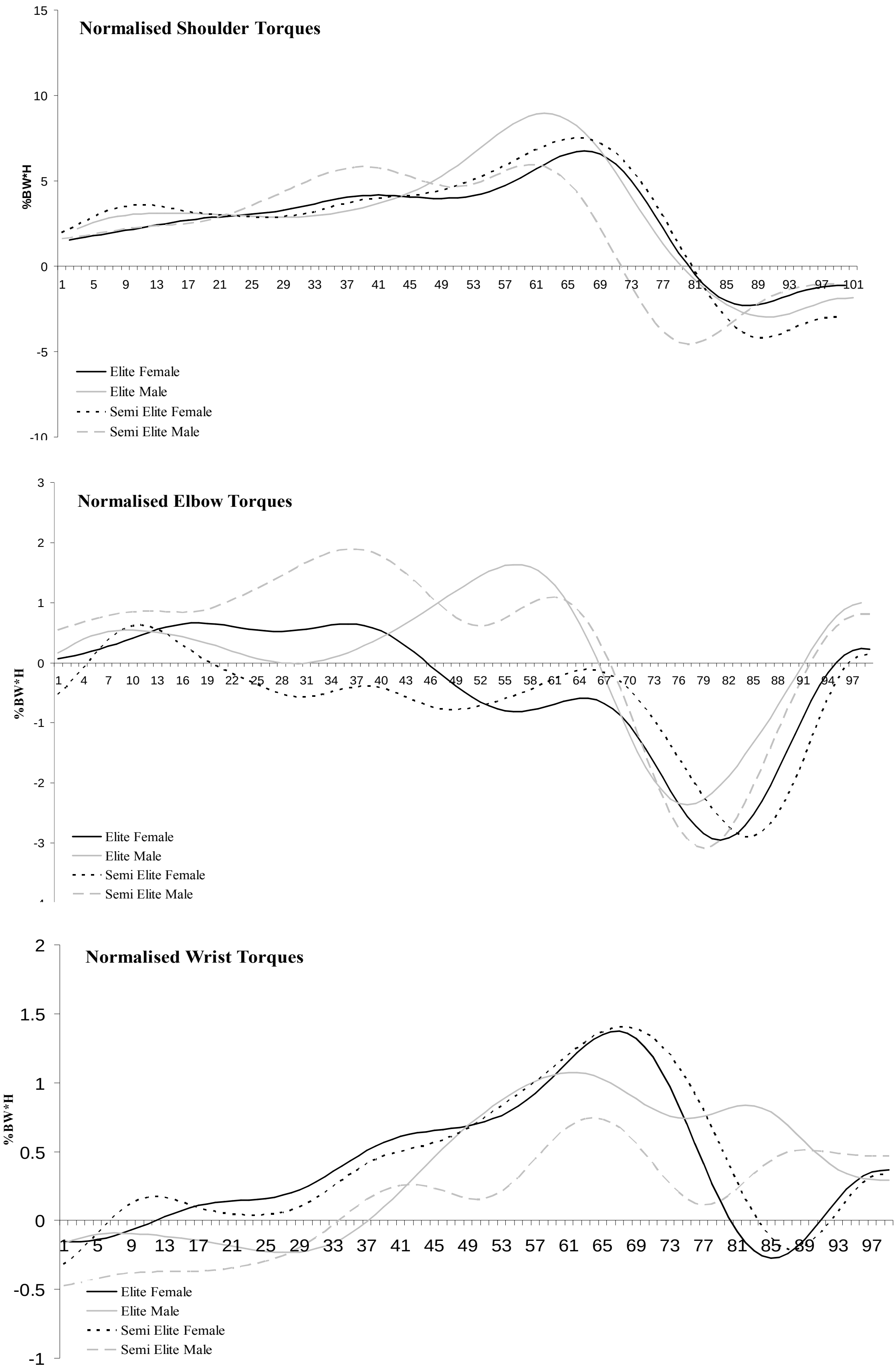


Figure 4.9: Torque-time graph of the shoulder, elbow and wrist

important factor in terms of motor correctional mechanisms (Bartlett, 2008) as well as injury prevention. Extension torques has been previously suggested to being able to help increase compression forces on the shoulder complex during high velocity movements (Barrentine et al., 1998) and thus help protect and ensure the joint was preserved during repetitive stress. Similar type of extension torques were also present at the elbow prior to release, as well as at the wrist, but at much smaller magnitudes. The wrist had minimal torques throughout the delivery, indicating it had little role in generating ball velocity. It is common for some bowlers to use wrist guards to 'lock' the wrist (Wiedman, 2006) to have more consistent motion by reducing joint degree of freedom. Now it appears to makes sense to do so.

The similar normalised torque patterns and peak values displayed between the groups was in agreement with the near similar kinematic patterns that was observed between the groups discussed earlier. All 30 of the bowlers were relatively of a high level, went through the same coaching development with the national bowling setup, hence, the similar techniques that were employed.

It was not possible to compare kinetic data from this study with bowlers from other studies as there was no previous published research done on ten pin bowling. Alternatively, when the generated torques was compared to another underarm movement – the windmill softball pitch, the patterns were rather similar. Peak shoulder and elbow extension torques also occurred near ball release in the windmill pitch (Werner et al., 2006, Barrentine et al., 1998).

When compared to data from Werner et al. (2006), their female Olympic pitchers had peak shoulder flexion torque of 4.5 %BW*H and peak extension torque of 22 %BW*H. Comparatively, the elite female bowlers from this study exhibited higher peak shoulder flexion torque (8.1 %BW*H) but lower peak extension (3.7 %BW*H). At the elbow region, the pitchers showed no flexion torques but had an extension torque of 13.0 %BW*H. Meanwhile, the elite female bowlers had 2.3 %BW*H flexion and 3.7 %BW*H extension torques at the elbow respectively. The higher flexion torques seen specifically in the shoulder region in bowling is explainable by the effort needed to move a significantly higher mass, as a bowling ball weighs 7 kg while a softball only weighs 0.17 kg. On the other hand, the pitchers showed higher extension torques compared to bowlers, which most likely stem from the higher peak angular velocities of 2190.0 deg/s that the pitchers generated (Werner et al., 2006), thus warranting a higher need for the pitchers to introduce more compressive forces near release. Comparatively, the elite female bowlers only generated velocities of 954.0 deg/s.

Finally, it was also interesting to relate this finding to the common assumption that the downswing during delivery was gravity driven (Benson, 2000) and bowlers only controlled the direction of swing. It has been shown from the analysis that this assumption was misleading. It could be seen in Figure 4.9 that joint torques were present entire swing motion. The gradual increase in shoulder torque indicated that the arm was actively being accelerated as opposed to free falling. The extension torques displayed in all joints also suggested that bowlers were actively controlling the swing near release.

In summary, it is apparent that joint torques in bowling are quite pronounced. Considering that Barrentine et al. (1998) suggested that torques about the shoulder region of between 3-7 %BW*H are sufficient to produce overuse injury, the elite and semi-elite bowlers were therefore constantly vulnerable to injury risk. Thus it is reasonable to state that bowling is not only a recreational activity, as at the higher levels the skills, finesse and risks involved are quite marked and on par with other competitive sports.

CHAPTER FIVE:
CONCLUSION AND IMPLICATIONS

Chapter 5: <u>Conclusion and Implications</u>

5.1 <u>Conclusion</u>

The objective of this study was to determine the critical parameters in the ten pin bowling delivery that was important for a good bowling performance. In the effort to achieve this goal, the first part of this study involved ten anthropometric measurements and seven strength tests. From these variables, a number of differences were found between the elite bowlers, semi-elite bowlers and the non-bowlers. On closer inspection, these differences mainly appear only between the bowlers and the non-bowlers. No significant differences were detected between elite and semi-elite bowlers, which were the main focus groups. There were also no identifiable critical parameters for good bowling performance, as this study was not able to successfully distinguish between good and excellent bowlers based on physical attributes alone. However, in terms of differences to the normal population, bowlers generally tended to be heavier, had longer limbs, had stronger forearm internal rotation and arm flexion.

For the second part of the study, a total of 43 discrete kinematic variables were extracted from the 3D motion analysis, from which it can be summed that the two bowling groups had similar patterns for the majority of segments with the exception of the shoulder and elbow region. The discriminant analysis revealed that there were three critical kinematic variables. To a certain extent it was possible to distinguish the playing level of bowlers utilising these variables alone, with the cross-validated classification estimating a 76.7% success rate.

From the discrete kinematic data, this study also looked at within-subject inter-trial variability to compare movement consistency. In total, 41 absolute variability variables were examined, of which a number of differences were observed between the elite and semi-elite bowlers, especially at the base (foot region) and the wrist, both of which are the most distal segments. The discriminant analysis highlighted four critical variability variables. Cross-validated classification revealed an estimated 76.7% success rate in distinguishing the playing level of bowlers utilising these variables alone.

With regards to the supplementary analysis, it was established that arm swing in bowling was not purely gravity driven as the bowlers actively accelerated the arm throughout the swing. In addition, the arm segment, in particular, the shoulder region contributes the most towards final ball velocity.

In conclusion, the critical parameters of delivery for good bowling performance were higher shoulder velocity at front foot strike, higher elbow velocity at release, lower wrist height at release, more consistent foot lateral position at front foot strike, more consistent wrist lateral position at release, more varied foot slide distance, and more varied wrist superior-inferior position at release.

Finally, as a consequence of the vast data gathered from this study, anthropometric and strength normative data, as well as kinematic and absolute variability measures for high level bowlers in Malaysia have been established and are readily available as a reference.

5.2 Implications

The structure and direction of this study were designed with the goal of producing results that have practical implications and applications for bowling coaches and bowlers themselves.

At the top level, there seem to be no advantage for any particular physical attributes, making it possible for bowlers of varying builds to reach the highest level. At the same time, it would not be misleading to suggest that bowlers and coaches pay particular attention to forearm/wrist internal rotators and the arm flexors during strength training. Overall though, as bowlers were different to the normal population in a number of physical aspects, there may be a case for specific scouting of potential bowlers. Bowling talent identification programs would probably have a better athlete base to build upon by selecting bigger built candidates that have relatively long limbs. This would probably make it easier to attain the desired ball velocity threshold to be a successful bowler.

In terms of delivery technique, bowlers should be advised to have fast shoulder angular velocities near mid-point of the arm swing with a correspondingly high elbow flexion velocity near ball release. Importantly, coaches should advocate a lower ball release height, specifically in the region of 30 to 35 cm.

Moreover, in line with common knowledge in bowling, bowlers need to be as consistent as possible in terms of lateral positioning. Specifically, the position of the slide foot and the position of the wrist near release need to be consistent. Conversely, coaches should encourage their bowlers, where needed, to vary their slide distance as well as the height of the wrist near release as these adjustments may be necessary for attaining certain ball release requirements.

Taking into consideration that teaching consistency in rapid motions is a challenging task; this study suggests the use of additional markers on the bowling lane during training to aid foot placement consistency. Where access to technology is possible, the use of projected laser lines on the lane is probably more logistically feasible. Additionally, to aid training for consistency of wrist position a custom wrist cuff apparatus with accelerometers or active marker is suggested. Both these suggestions are under consideration for intellectual property applications at the time of submission of this thesis.

5.3 Future Research Direction

As the anthropometric data from this current study was limited to length and breadth measurements, a comprehensive anthropometrical study in the future may include segment girths and skinfold measurements. Besides this, research looking at the influence of forearm/wrist rotation to ball spin and performance may be important as it will widen the knowledge base established by this current study. Alternately, investigations into the kinematics distinctions of the different bowling styles would be interesting as it may reveal how different technique affected ball delivery and performance. Finally, this study reported a number of differences between male and female bowlers, even though the bowling scores were similar. However, discussions were limited as gender differences were not a main concern for this study. Therefore, it would be of great interest to examine how males and females achieved the same performance level, despite differences in kinematics and movement variability.

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APPENDIX

Appendix 1

Preliminary Questionnaire for Coaches
on the Important Parameters of the Delivery in Ten Pin Bowling

Greetings! This questionnaire is part of a postgraduate research project on ten pin bowling delivery. The purpose of these questions is to gauge the opinions of coaches on issues related to the delivery phase in bowling.

Some questions are subjective and open ended while others are based on a rating scale of 1 to 5. With 1 being Not Important and 5 being Very Important, you will have to circle the appropriate number. Please assume that the bowler in question is right handed and is only delivering first balls (not spare deliveries).

Please do not rush through the questions; take your time to answer and if necessary playback some old bowling videos to refresh your memory. Also, please do not hesitate to contact me at rizal@um.edu.my or 6012-2962707 if you have any queries. Thank you!

1. How important is it to release exactly at the bottom end of the downward swing?

   (Not Important)⟵ **1** **2** **3** **4** **5** ⟶(Very Important)

2. Which body segment is used as the marker for the release point? *For example: should they release before the ankle at the final step.*

   ____

   ____

3. What is the approximate maximum height for the backswing (relative to the bowler)? *For example: should the ball reach the head height.*

   ____

   ____

4. When should the maximum backswing occur? *For example: should it be at the same time as the foot contact on the second last step.*

   ____

   ____

5. How important is the follow through in the bowling delivery?

   (Not Important)⟵ **1** **2** **3** **4** **5** ⟶(Very Important)

6. In which direction should the hand swing be in the follow through? *For example: should it swing exactly straight in front*

   ____

   ____

7. How important is the head position during release?

(Not Important)⟵ **1** **2** **3** **4** **5** ⟶(Very Important)

8. Which direction should the head be facing and what should they look at during release?

____

____

9. How important is the opposing arm position at release?

(Not Important)⟵ **1** **2** **3** **4** **5** ⟶(Very Important)

10. In what position (relative to the bowler) should the opposite arm be at release? *For example: should it be in line with the sliding leg*

____

____

11. How important is the forward/leading leg slide at release?

(Not Important)⟵ **1** **2** **3** **4** **5** ⟶(Very Important)

12. Describe how and when should the forward/leading leg slide start and end?

____

____

13. How important is the opposite leg slide at release?

(Not Important)⟵ **1** **2** **3** **4** **5** ⟶(Very Important)

14. Describe how and when should the opposite leg slide start and end? -

____

____

15. How important is it to have the exact same timing on every delivery?

(Not Important)⟵ **1** **2** **3** **4** **5** ⟶(Very Important)

16. How do you identify the proper timing of movements with your bowlers? *For example: the first step leg contact should correspond with the start of backswing*

____

____

17. Please describe any other points relating to the release that you think is important.

____

____

____

____

Appendix 2

Participant Background Information and Consent Form

NAME: ____ AGE: __________

I/C NO: ____ GENDER: _______

DOMINANT SIDE: __________________________________ HEIGHT: ________

ADDRESS: ____ WEIGHT: _______

____ BMI: __________

TEL NO & EMAIL: ____

BOWLING STYLE: ___________________________ AVERAGE SCORE: ______

HIGHEST LEVEL: ______________________________ FROM: ______________

BEST ACHIVEMENT: __________________________ HIGHEST SCORE: _______

STARTED BOWLING: _________________ YEARS IN ACTIVE TRAINING: ____

WEIGHT OF BALL: ______________ TYPE: ________ STEPS TAKEN: _________

Circle your answer. If in doubt circle 'YES'

Have you ever been diagnosed to have a heart problem?	YES / NO
Have you ever been diagnosed with high blood pressure?	YES / NO
Have you ever had muscle, bone or joint injury or illness	YES / NO
Do you have any other illness or anomalies?	YES / NO
Are you carrying any injuries?	YES / NO
Are you using any prescription drugs at the moment?	YES / NO
Do you have any other problems related to physical activity?	YES / NO

If you answered YES to any of the above questions, please consult the instructor or your doctor before commencing any tests.

I UNDERSTAND THAT I AM PARTICIPITATING IN THESE TESTS ON MY OWN FREE WILL. I AM AWARE THAT ALTHOUGH UNIVERSITY OF MALAYA, SPORTS CENTRE AND THE INSTRUCTOR CONDUCT THE TESTS IN THE SAFEST POSSIBLE MANNER, THERE ARE STILL SOME RISKS INVOLVED. I WILL NOT HOLD UNIVERSITY OF MALAYA, MTBC, SPORTS CENTRE OR THE INSTRUCTOR LIABLE SHOULD ANY ACCIDENT / INJURY OCCUR DURING THE TESTS.

SIGNATURE: ………………………………… **DATE:** ……………

<u>**Appendix 3**</u>

Concurrent Validity and Test-retest Reliability of the Isometric Strength Tests

Middle finger to thumb pinch			Third finger to thumb pinch			Isometric arm flexion			Hand Grip	1RM seated
Trial 1	Trial 2	Max	Trial 1	Trial 2	Max	Trial 1	Trial 2	Max	Dynamometer	bench arm curl
3.7	3.7	3.7	3.0	2.8	3.0	12.3	12.9	12.9	35.2	7.8
3.2	3.0	3.2	2.5	2.6	2.6	10.6	9.8	10.6	33.0	7.2
2.5	2.3	2.5	2.4	2.4	2.4	8.4	9	9.0	29.4	6.2
2.5	2.6	2.6	2.0	2.1	2.1	10.8	10.2	10.8	28.8	7.2
2.2	2.2	2.2	1.5	1.6	1.6	7.6	7.1	7.6	27.4	5.8
1.9	2.0	2.0	1.5	1.5	1.5	7.6	7.0	7.6	25.4	6.0
3.4	3.5	3.5	1.7	1.5	1.7	11.4	11.7	11.7	30.6	7.6
4.0	4.1	4.1	2.4	2.5	2.5	12.1	11.5	12.1	36.8	7.8
2.9	2.8	2.9	3.2	3.1	3.2	8.0	7.6	8.0	31.2	6.0
3.4	3.5	3.5	2.4	2.5	2.5	12.0	12.6	12.6	34.6	7.6
3.7	3.7	3.7	3.1	2.8	3.1	15.7	15	15.7	35.8	8.2
3.9	3.8	3.9	3.3	3.1	3.3	14.4	14.2	14.4	36.6	8.4
2.7	2.6	2.7	2.6	2.5	2.6	11.7	11.1	11.7	29.2	7.0
3.6	3.5	3.6	3.5	3.2	3.5	9.9	10.0	10.0	34.4	7.0
3.0	3.1	3.1	1.6	1.8	1.8	10.7	9.9	10.7	32.0	7.2
2.7	2.8	2.8	2.0	2.2	2.2	10.9	10.0	10.9	29.6	7.2
3.3	3.5	3.5	1.8	1.9	1.9	13.0	12.2	13.0	31.8	8.2
2.6	2.8	2.8	2.4	2.5	2.5	14.5	13.4	14.5	29.4	7.5
1.9	2.1	2.1	1.4	1.3	1.4	6.4	6.8	6.8	25.0	5.0
3.8	3.8	3.8	3.0	2.6	3.0	15.9	15.3	15.9	36.0	8.5

Pilot test was conducted with 20 sedentary male university students. Middle finger to thumb and third finger to thumb pinch strength was tested against hand grip dynamometer scores, resulting in a correlation coefficient of 0.96 and 0.75 respectively. Isometric arm flexion was tested against the 1RM seated bench arm curl, resulting in a correlation coefficient of 0.94.

Test-retest reliability correlation coefficient between trial one and two for middle finger to thumb, third finger to thumb pinch and arm flexion test was 0.98, 0.97 and 0.98 respectively.

Appendix 4

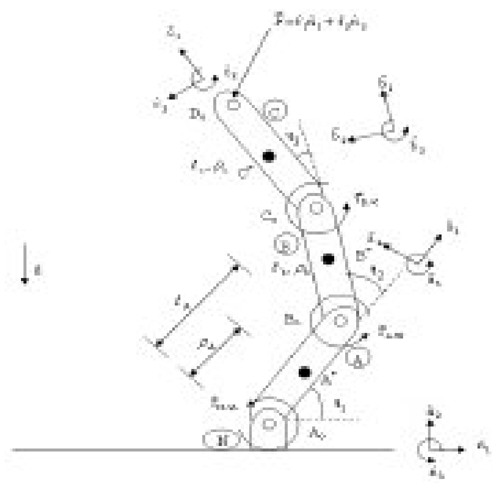
Body Segment Parameters from Data Gathered by Winter (2005)

Segment	Definition	Segment Weight/Total Body Weight	Center of Mass/ Segment Length		Radius of Gyration/ Segment Length			Density
			Proximal	Distal	C of G	Proximal	Distal	
Hand	Wrist axis/knuckle II middle finger	0.006 M	0.506	0.494 P	0.297	0.587	0.577 M	1.16
Forearm	Elbow axis/ulnar styloid	0.016 M	0.430	0.570 P	0.303	0.526	0.647 M	1.13
Upper arm	Glenohumeral axis/elbow axis	0.028 M	0.436	0.564 P	0.322	0.542	0.645 M	1.07
Forearm and hand	Elbow axis/ulnar styloid	0.022 M	0.682	0.318 P	0.468	0.827	0.565 P	1.14
Total arm	Glenohumeral joint/ulnar styloid	0.050 M	0.530	0.470 P	0.368	0.645	0.596 P	1.11
Foot	Lateral malleolus/head metatarsal II	0.0145 M	0.50	0.50 P	0.475	0.690	0.690 P	1.10
Leg	Femoral condyles/medial malleolus	0.0465 M	0.433	0.567 P	0.302	0.528	0.643 M	1.09
Thigh	Greater trochanter/femoral condyles	0.100 M	0.433	0.567 P	0.323	0.540	0.653 M	1.05
Foot and leg	Femoral condyles/medial malleolus	0.061 M	0.606	0.394 P	0.416	0.735	0.572 P	1.09
Total leg	Greater trochanter/medial malleolus	0.161 M	0.447	0.553 P	0.326	0.560	0.650 P	1.06
Head and neck	C7–T1 and 1st rib/ear canal	0.081 M	1.000	— PC	0.495	0.116	— PC	1.11
Shoulder mass	Sternoclavicular joint/glenohumeral axis	—	0.712	0.288	—	—	—	1.04
Thorax	C7–T1/T12–L1 and diaphragm*	0.216 PC	0.82	0.18	—	—	—	0.92
Abdomen	T12–L1/L4–L5*	0.139 LC	0.44	0.56	—	—	—	—
Pelvis	L4–L5/greater trochanter*	0.142 LC	0.105	0.895	—	—	—	—
Thorax and abdomen	C7–T1/L4–L5*	0.355 LC	0.63	0.37	—	—	—	—
Abdomen and pelvis	T12–L1/greater trochanter*	0.281 PC	0.27	0.73	—	—	—	1.01
Trunk	Greater trochanter/glenohumeral joint*	0.497 M	0.50	0.50	—	—	—	1.03
Trunk head neck	Greater trochanter/glenohumeral joint*	0.578 MC	0.66	0.34 P	0.503	0.830	0.607 M	—
Head, arms, and trunk (HAT)	Greater trochanter/glenohumeral joint*	0.678 MC	0.626	0.374 PC	0.496	0.798	0.621 PC	—
HAT	Greater trochanter/mid rib	0.678	1.142	—	0.903	1.456	—	—

Appendix 5

Computational Methods for an Arm Model (Ariff & Rambely, 2009)

Figure 1: Planar three-link kinematic chain of an arm with an endpoint.



Notation:

○ = joints

● = centre of mass

(A) = segment A (shoulder-elbow)

(B) = segment B (elbow-wrist)

(C) = segment C (wrist-racquet)

A^*, B^*, C^* = centre of mass of segments A, B and C respectively

$\hat{n}_1, \hat{n}_2, \hat{n}_3, \hat{a}_1, \hat{a}_2, \hat{a}_3, \hat{b}_1, \hat{b}_2, \hat{b}_3, \hat{c}_1, \hat{c}_2, \hat{c}_3$ = mutually orthogonal unit vector

ρ_A, ρ_B, ρ_C = distances of centre of mass from their proximal ends

ℓ_A, ℓ_B, ℓ_C = length of segments

$\bar{\tau}_{N/A}, \bar{\tau}_{A/B}, \bar{\tau}_{B/C}$ = torques of each joints

$\bar{F} = f_1\hat{n}_1 + f_2\hat{n}_2$ = endpoint force of arbitrary direction and magnitude

First, the angular velocities of bodies A, B and C with respect to reference frame N are determined to be,

$$N_{\omega}A = \dot{q}_1\hat{a}_3 \quad (3.1)$$

$$N_{\omega}B = (\dot{q}_1 + \dot{q}_2)\hat{b}_3 \quad (3.2)$$

$$N_{\omega}C = (\dot{q}_1 + \dot{q}_2 + \dot{q}_3)\hat{c}_3 \quad (3.3)$$

Likewise, the angular accelerations are,

$$N_{\alpha}A = \ddot{q}_1\hat{a}_3 \quad (3.4)$$

$$N_{\alpha}B = (\ddot{q}_1 + \ddot{q}_2)\hat{b}_3 \quad (3.5)$$

$$N_{\alpha}C = (\ddot{q}_1 + \ddot{q}_2 + \ddot{q}_3)\hat{c}_3 \quad (3.6)$$

The velocities of points A^*, B_o, B^*, C_o, C^* and D_o are found to be,

$$N_{v}A^* = \rho_A\dot{q}_1\hat{a}_2 \quad (3.7)$$

$$ {}^{N}\vec{v}^{B_O} = \ell_A \dot{q}_1 \hat{a}_2 \tag{3.8} $$

$$ {}^{N}\vec{v}^{B^*} = \ell_A \dot{q}_1 \hat{a}_2 + \rho_B (\dot{q}_1 + \dot{q}_2) \hat{b}_2 \tag{3.9} $$

$$ {}^{N}\vec{v}^{C_O} = \ell_A \dot{q}_1 \hat{a}_1 + \ell_B (\dot{q}_1 + \dot{q}_2) \hat{b}_2 \tag{3.10} $$

$$ {}^{N}\vec{v}^{C^*} = \ell_A \dot{q}_1 \hat{a}_2 + \ell_B (\dot{q}_1 + \dot{q}_2) \hat{b}_2 + \rho_C (\dot{q}_1 + \dot{q}_2 + \dot{q}_3) \hat{c}_2 \tag{3.11} $$

$$ {}^{N}\vec{v}^{D_O} = \ell_A \dot{q}_1 \hat{a}_2 + \ell_B (\dot{q}_1 + \dot{q}_2) \hat{b}_2 + \ell_C (\dot{q}_1 + \dot{q}_2 + \dot{q}_3) \hat{c}_2 \tag{3.12} $$

The accelerations of mass location A*, B* and C* are,

$$ {}^{N}\vec{a}^{A^*} = -\rho_A \dot{q}_1^2 \hat{a}_1 + \rho_A \ddot{q}_1 \hat{a}_2 \tag{3.13} $$

$$ {}^{N}\vec{a}^{B^*} = -\ell_A \dot{q}_1^2 \hat{a}_1 + \ell_A \ddot{q}_1 \hat{a}_2 - \ell_B (\dot{q}_1 + \dot{q}_2)^2 \hat{b}_1 + \rho_B (\ddot{q}_1 + \ddot{q}_2) \hat{b}_2 \tag{3.14} $$

$$ \begin{aligned} {}^{N}\vec{a}^{C^*} = & -\ell_A \dot{q}_1^2 \hat{a}_1 + \ell_A \ddot{q}_1 \hat{a}_2 - \ell_B (\dot{q}_1 + \dot{q}_2)^2 \hat{b}_1 + \ell_B (\ddot{q}_1 + \ddot{q}_2) \hat{b}_2 \\ & - \rho_C (\dot{q}_1 + \dot{q}_2 + \dot{q}_3)^2 \hat{c}_1 + \rho_C (\ddot{q}_1 + \ddot{q}_2 + \ddot{q}_3) \hat{c}_2 \end{aligned} \tag{3.15} $$

Using Kane's method, the angular velocities and the velocities of points can be factored out to obtain partial angular velocities and partial velocity vectors. To factor these velocities, quantities called $u_i \equiv \dot{q}_i$ (i = 1, 2, 3) are introduced. u_i is known as the i-th generalized speed of the system.

From equation (3.1), (3.2), and (3.3), the first, second and third partial angular velocities for segment A, B and C are then obtained respectively as,

$$ {}^{N}\vec{\omega}^{A} = (\vec{a}_3) u_1 + (\vec{0}) u_2 + (\vec{0}) u_3 \tag{3.16} $$

$$ {}^{N}\vec{\omega}_1^{A} = \vec{a}_3 \,;\; {}^{N}\vec{\omega}_2^{A} = \vec{0} \,;\; {}^{N}\vec{\omega}_3^{A} = \vec{0} \tag{3.17, 3.18 \& 3.19} $$

$$ {}^{N}\vec{\omega}^{B} = (\hat{b}_3) u_1 + (\hat{b}_3) u_2 + (\vec{0}) u_3 \tag{3.20} $$

$$ {}^{N}\vec{\omega}_1^{B} = {}^{N}\vec{\omega}_2^{B} = \hat{b}_3 \,;\; {}^{N}\vec{\omega}_3^{B} = \vec{0} \tag{3.21, 3.22 \& 3.23} $$

$$ {}^{N}\vec{\omega}^{C} = (\hat{c}_3) u_1 + (\hat{c}_3) u_2 + (\hat{c}_3) u_3 \tag{3.24} $$

$$ {}^{N}\vec{\omega}_1^{C} = {}^{N}\vec{\omega}_2^{C} = {}^{N}\vec{\omega}_3^{C} = \hat{c}_3 \tag{3.25, 3.26 \& 3.27} $$

The partial velocity vectors are determined in the same way as the partial angular velocities.

$$ {}^{N}\vec{v}^{A^*} = (\rho_A \hat{a}_2) u_1 + (\vec{0}) u_2 + (\vec{0}) u_3 \tag{3.28} $$

$$ {}^{N}\vec{v}_1^{A^*} = \rho_A \hat{a}_2 \,;\; {}^{N}\vec{v}_2^{A^*} = \vec{0} \,;\; {}^{N}\vec{v}_3^{A^*} = \vec{0} \tag{3.29, 3.30 \& 3.31} $$

$$ {}^{N}\vec{v}^{B^*} = (\ell_A \hat{a}_2 + \rho_B \hat{b}_2) u_1 + (\rho_B \hat{b}_2) u_2 + (\vec{0}) u_3 \tag{3.32} $$

$$ {}^{N}\vec{v}_1^{B^*} = \ell_A \hat{a}_2 + \rho_B \hat{b}_2 \,;\; {}^{N}\vec{v}_2^{B^*} = \rho_B \hat{b}_2 \,;\; {}^{N}\vec{v}_3^{B^*} = \vec{0} \tag{3.33, 3.34 \& 3.35} $$

$$ {}^{N}\vec{v}^{C^*} = (\ell_A \hat{a}_2 + \ell_B \hat{b}_2 + \rho_C \hat{c}_2) u_1 + (\ell_B \hat{b}_2 + \rho_C \hat{c}_2) u_2 + (\rho_C \hat{c}_2) u_3 \tag{3.36} $$

$$ {}^{N}\vec{v}_1^{C^*} = \ell_A \hat{a}_2 + \ell_B \hat{b}_2 + \rho_C \hat{c}_2 \,;\; {}^{N}\vec{v}_2^{C^*} = \ell_B \hat{b}_2 + \rho_C \hat{c}_2 \,;\; {}^{N}\vec{v}_3^{C^*} = \rho_C \hat{c}_2 \tag{3.37, 3.38 \& 3.39} $$

$$ {}^{N}\vec{v}^{D_O} = (\ell_A \hat{a}_2 + \ell_B \hat{b}_2 + \ell_C \hat{c}_2) u_1 + (\ell_B \hat{b}_2 + \ell_C \hat{c}_2) u_2 + (\ell_C \hat{c}_2) u_3 \tag{3.40} $$

$$ {}^{N}\vec{v}_1^{D_O} = \ell_A \hat{a}_2 + \ell_B \hat{b}_2 + \ell_C \hat{c}_2 \,;\; {}^{N}\vec{v}_2^{D_O} = \ell_B \hat{b}_2 + \ell_C \hat{c}_2 \,;\; {}^{N}\vec{v}_3^{D_O} = \ell_C \hat{c}_2 \tag{3.41, 3.42 \& 3.43} $$

Generalized active forces and generalized inertia forces are then formulated for segments A, B and C. To form the generalized active forces, vector dot products between the partial velocities of points and the forces acting at those points are computed and added together. Additionally, dot products between partial angular velocities and torques are added together and summed together with the previous result. After computing the generalized active forces, the generalized inertia forces are calculated next. These are composed of the dot products between the partial velocities of the mass centre and the inertial forces there, as well as the dot products between the partial angular velocities and the inertial torques. The generalized active forces and the generalized inertial forces represented by the equations are summarized as follows,

$F_1 + F_1^* = 0; F_1 = - F_1^*$ (3.44 & 3.45)

$F_2 + F_2^* = 0; F_2 = -F_2^*$ (3.46 & 3.47)

$F_3 + F_3^* = 0; F_3 = -F_3^*$ (3.48 & 3.49)

where F_1, F_2 and F_3 are generalized active forces and F_1^*, F_2^* and F_3^* are generalized inertia forces.

These dynamics equations can be represented in matrices form,

$$M\bar{\ddot{Q}} = \bar{G} + \bar{E} + \bar{T}, \quad (3.50)$$

where M: mass matrix

$\bar{\ddot{Q}}$: angular acceleration vectors

$\bar{G}$: vector of moments from gravitational forces

$\bar{E}$: vector of moments from external forces, and

$\bar{T}$: vector of applied torques.