An Overview on the Performance of Sprinters with Lower Limb Amputation/Impairment in Paralympic Games

by

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ABSTRACT

The inclusion of technology in sport has been the core of many debates with regard to the fairness of sport. Many of the experts believe that the use of these technologies gives an unfair advantage to those who are using them, which is in contradiction with the nature of professional competitive sports (sport discipline). Over the last few decades carbon fibre prosthesis has developed considerably and it has facilitated running activity for amputees. The evaluation of such technologies is now urgently required as the use of carbon fibre prosthesis is now being investigated through justice and legal systems to determine the participation of amputees using them at professional sports events.

This thesis attempts to provide some answers for the controversial issues at professional running at the Paralympic Games based on some statistical analyses. The available historical data in the Paralympics' website has been considered as the source of information and some statistical tools have been applied in order to find some answers for the hypotheses raised in this research.

The results of this thesis indicate that bilateral amputees in running activity in Paralympic Games have an advantage comparing to unilateral (as they take advantage of symmetry in their running activity) especially in long running competition (400m).It also proves that the amputees below knee run faster than those who run with above knee amputation. In order to make the Paralympic games equitable, there has been a lot of change in the classification system since its introduction. Classification used to be only based on a medical examination, while in the modern system it is based on the functional ability of the lost (or impaired) limb. Nevertheless, the results of this research indicate that in some cases these categories are not fair and they need to be revised. The results of this research indicates that the T43 and T44 classifications need to be competing in two separate groups as the bilateral amputees take advantage of symmetry in their running activity.

The results of this thesis illustrate that the introduction of Energy Storage and Return foot (ESR), made a breakthrough in prosthesis design. ESR foot has a higher efficiency compared to the classic prosthesis. Through the help of ESR foot, Paralympians run faster and generally it facilitates the running activity for them.

Changing the perception of ordinary people towards disability has been one of the key aims of this research. In order to do so, some analyses have been provided to indicate the differences between the Olympics and Paralympics. The historical data in these two big sport events has been considered as the source of information to address this issue. The performance of the Paralympians and Olympians has been compared through diagrams and tables and it illustrates that, although there have been some differences between the results of

these two sports events (with the focus on running exercise), the gap is getting smaller and smaller. Technological developments and increased level of participation has been introduced as the primary reasons for making this gap smaller. Representing the results of this research can potentially change the people's attitude towards disability; thinking of what disabled people are actually capable of doing, rather than what they cannot do.

Forecasting can provide some valuable information for the decision makers and it can illustrate where the sport is going to. So the last chapter of this thesis, provide a forecast for 2015 Paralympic Games (running exercise) based on the novel approach of Singular Spectrum Analysis (SSA). The results of forecast indicate that the Paralympians will enhance their performance in 2015 Paralympic Games.

Aims:

- Identifying the impact of number of blades in running exercise
- Evaluating the fairness of Paralympic classification in running exercise.
- Representing the impact of technology enhancement in the outcome of the competition for the Paralympians.
- A comparison between the results of Paralympic and Olympic in running exercise.

Objectives:

- Indicating the advantage of bilateral amputees in running activity comparing to unilateral amputees based on some statistical analyses and introducing the mechanical differences between the bilateral and unilateral lower limb amputees.
- Providing a recommendation for governing bodies in Paralympic Games regarding to the separation of T43 and T44 in future games based on statistical analyses.
- Indicating the significant differences between running on ESR foot and classic prosthesis based on statistical analyses.
- Representing the fact that the gap between Paralympic and Olympic is getting smaller and smaller based on historical data, and Introducing the main reasons which make Paralympic Games different from Olympics.

TABLE OF CONTENTS

Chapters:

LIST OF TABLES:

LIST OF FIGURES:

CHAPTER 1: THE HISTORY OF PARALYMPIC GAMES AND THE USE OF PROSTHESIS IN PROFESSIONAL RUNNING

1.1 INTRODUCTION:

This chapter attempts to provide a brief history of the Paralympic Games and introduces the governing bodies and their goals in this huge sports event. At the beginning a brief history of the Paralympic Games has been included and it introduces how the major governing bodies in this huge sport event for disabled people has shaped, and what are their roles and responsibilities. Also a brief history of the prosthesis foot has been included and the major developments in terms of design which made a significant difference in running activity for the disabled people has been introduced. While this chapter attempts to introduce the major mechanical differences between modern and classic prostheses and it shows that how the concept of energy storage and return facilitated running activity for amputees, the hypothesis has been proved based on some statistical tools in the next chapters. In addition the acceptability and viability of the inclusions of technology in sport has been discussed and the accepted frameworks and the scenarios which determine what type of technology can be applied in professional sport has been introduced.

In the last few years the fairness of professional running at the Paralympic Games has been seriously criticized. For example in 2005 bilateral amputee Oscar Pistorius was investigated due to the claim of having a mechanical advantage over able-bodied athletes (Dyer et al. 2010) and in another case in 2012, Allan Oliveira was criticised by Pistorius after 200m final for using the limbs that were alleged advantageous due to their length (Camporesi 2008). This chapter attempts to represents where the core of these debates is, and it tries to illustrate how legislation in terms of use of prosthesis can help to the fairness of sport.

1.2 PARALYMPIC GAMES:

For some people with disability, competitive sports can provide a vehicle for leveling out some of the inequalities that they have been facing in their day to day life while giving them the opportunity to push themselves beyond their limit. Competitive sports can play a key role in the life of an individual with a disability, which eventually can result in a better quality of life. Paralympic Games is the most important event for disabled sportsmen and women. It provides an organized structure for the participation of disabled people in different sporting fields.

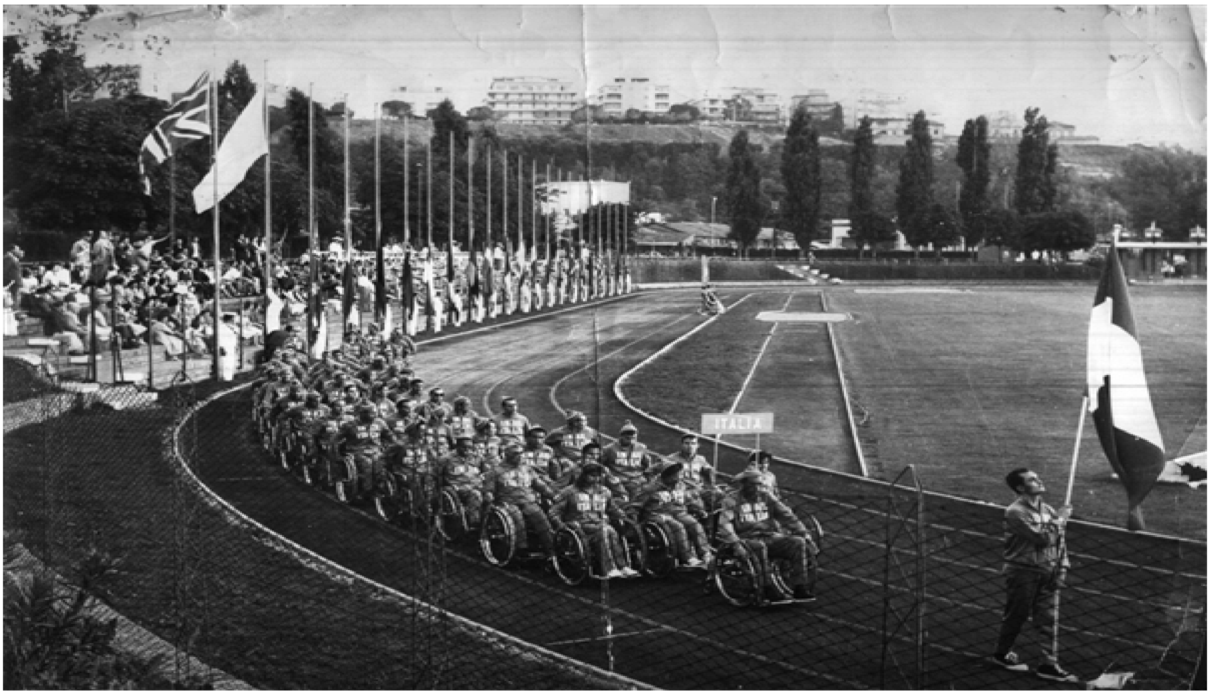

Figure 1: Opening ceremonies of 1960 Paralympic Games (www.spinalcord.org)

Sport for athletes with an impairment has existed for more than 100 years, however it was not until Second World War that it was widely introduced with the purpose of assisting the large number of veterans and civilians who had been injured during war time. The first organized form of sport for disabled people was held in 1948 along with the London Olympic Games and it was only for disabled people who used wheelchair and it was called Stoke Mandeville Games (Gold & Gold 2007). These games were later named the Paralympic Games with the first being held in 1960 in Rome. Twenty three nations and four hundred athletes competed against each other on this occasion (Sainsbury 2004).

The Paralympics cover six disability groups- athletes with intellectual disability, athletes with cerebral palsy, athletes with visual impairments, athletes with spinal cord injuries, Les Autres (French for “the others”) and athletes with amputation (Gold & Gold 2007). While there are several organized form of competition for disabled people, but Paralympic Games form the pinnacle for athletic excellence (Dyer 2013). The Paralympic Games now take place every four years (Sainsbury, 2004) in the two forms of summer and winter games. Today Paralympic Games have been held in 28 different sports fields. Athletics as a sporting discipline forms a key part of the Paralympic Games program and attracts the largest number of spectators (IPC 2013). Structured competition involving running with a lower-limb amputation has taken place consistently since 1976 (Dyer 2013).

Initially Paralympic Games was governed through consulting with several smaller organizations each of them with their own interest for a particular type of disability (Kiomourtzoglou & Politis 2002; Legg & Steadward 2011). In 1982 the need to coordinate Paralympics was recognized and the International Coordinating Committee Sport for Disabled (ICC) was created (Gold & Gold 2007). The major intend of creating this institute was collaborating and corresponding with Olympics governing body (IOC) as one umbrella organization rather than several smaller ones (Legg & Steadward 2001). In 1998, the International Paralympic Committee (IPC) was created (Kiomourtzoglou & Politis 2002) which is the governing body of sports for athletes with a disability (Bailey 2008). IPC organizes the Paralympic Games and it acts as the international federation for nine sports. The IPC was formed in order to extend and stabilize the world of elite sports for disabled people and is one of the most dynamic and the largest sports organizations in the world which comprises the vast majority of athletes with a disability (Bailey 2008).

Running Paralympic Games benefits society. This can be seen from the results from a study conducted by UK HM Government in 2012 after the Paralympic Games. The results of their research indicate that 81% of the people surveyed believed the games had a positive effect on how disabled people are viewed by the British public (HM Government 2013).Other positive effects identified were increased participation in sports and increasing accessibility on transport systems (in venues and other environments) (HM Government 2013). Another study completed by the House of Lords concluded that running these games could change the perception of disability in society (House of Lords 2013).

1.3 PROSTHESIS:

The word prosthesis come from the Greek language which means addition (Gutfleisch 2007). Prosthesis mainly has been used to help patients to have a better quality of life (Gutfleisch 2003) or replace the missing anatomical structure (Hillery & Strike 2001). In the other words the use of prosthesis will result in improving comfort, reducing energy expenditure and improving stability (Gutfleisch 2003).

The first written record of amputation is the Indian poem “Rig-Veida” and it was between 3500 and 1800 BC and it describes the warrior queen who lost her leg in a battle and it was fitted with an iron prosthesis (Cantos 2005; Thurston 2007). In early history the majority of amputations occurred as the result of war injuries, legal punishment, and religious sacrifices (Padula 1987). Peg leg or hand hook were early forms of prosthesis in history which were some rudimentary devices in order to replace the missed anatomical part of body (Friedmann 1978).

Major advances in prosthesis design happened during the Renaissance period, the American Civil War, and the two world wars with the aim of recovering the limb function (Tang et al. 2008). SACH foot is as an example which initially was devised by JE Hanger, a Southern soldier during the American Civil War (Tang et al. 2008). SACH is an abbreviation for “solid-ankle, cushioned heel”. Awareness of the importance of prosthesis during this period resulted in building new research institutes in this field and the public support for these research institutes led to the rapid development of modern prosthesis technology using innovative materials and designs (Tang et al. 2008).

Over the last 20 years along with the development of carbon fibre prosthesis, amputee sport performance has greatly improved (Nolan 2008). As the margins between winning and losing become smaller, athletes have increasingly been relying on the prosthesis technology in order to give them an advantage over other athletes and break existing records (Nolan 2008).

After the introduction of SACH foot in the late 1950s, the prosthesis foot did not change much (in terms of design an material) until the early 1980s (Nolan 2008). A more lightweight, flexible and strong material was introduced in order to make a foot which facilitated sport participation. When the body weight moves over this flexible foot, it compresses and energy is stored. When the weight shifts off from the foot, the structure returns to its original shape. This foot was named Energy Storage and Return (ESR) foot and it provides a push-off and return energy as it decompresses (Nolan, 2008). ESR foot has been designed to improve amputee gait by storing and releasing elastic energy during stance phase (Fey et al. 2013).

The ESR was first seen in elite sport at the 1988 Paralympic Games (Pailler et al. 2004). 1n 1992 the prosthesis heel for some athletes was removed (Pailler et al. 2004). Since 1992 several different sprint foot designs has been available with a slight change, but the similar basic shape.

The introduction of Energy Storage and Return foot (ESR) had an evolutionary impact on the running activity. In order to illustrate the differences between ESR feet and classic prostheses, the efficiency of them can be compared. The efficiency in a prosthesis can be defined as:

$$\frac{\text{Enery Returned}}{\text{Energy Stored}} \times 100$$

Energy is the capacity to work and there are different ways to calculate mechanical energy. Energy can be calculated from joint mechanics during gait analysis (Geil 2000). Energy storage and returned can be calculated as the integral of ankle power output (Pailler et al. 2004; Geil 2000; Czerniecki 1991) .No prosthetic feet has the efficiency of 100% as a result of friction or energy loss such as noise and heat (Nolan 2008). The results of some studies indicates that the human ankle provides substantially more work than any other joint in the lower limb (Geil 2000; Winter 1983). By using the above equation the human ankle has the energy efficiency of 241% during running at 2.8 m s^{-1} (Czerniecki 1991). In the human body storage and return energy occurs in the Achilles tendon and longitudinal arch of the foot and active plantar flexion (Mokha et al. 2007). It has been reported that SACH foot has an energy efficiency of 31% and flex foot 84% during running at 2.8 m s^{-1} (Czerniecki 1991). The results of these researches show that although ESR foot exhibit more energy efficiency comparing to other types of prostheses, but still unable to provide anywhere near the range of that of the human foot.

The basic components of a modern below knee prosthesis are liner, socket, pylon and foot.

Figure 2, represents different parts of a modern prosthesis.

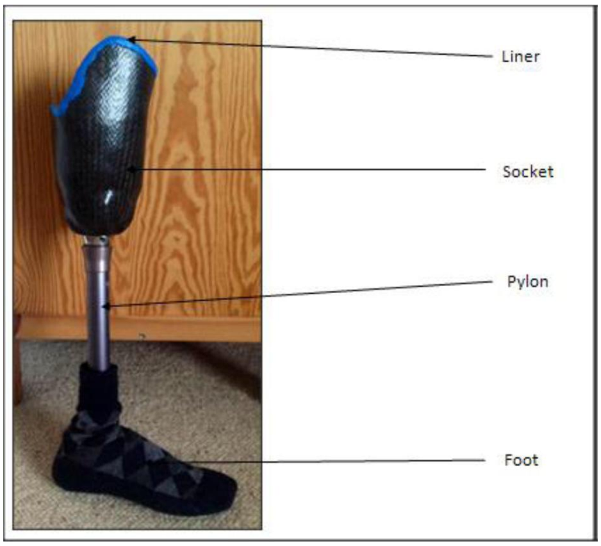

Figure 2: Parts of a modern prosthesis

Liner is often made of visco-elastic material (Lewis et al. 1996) such as silicon or gel (Webster et al, 2001) and it rolls over the top of the residual limb. The limb and liner then are inserted into the socket. The socket transmits the forces between the residual limb and prosthesis itself (Powelson & Yang 2012). The socket has to get satisfactory load transmission, stability and efficient control of mobility. The limb is held inside the socket by means of suction and suspension and it will support prosthesis when there is no weight being placed upon it (Powelson & Yang 2012). The Pylon or shank is the third part which is below socket and contributes to the limb length. Then the shank has been attached to foot assembly, which can be shaped or derived from different materials. This design is according to the user's need and prosthesis application (Powelson & Yang 2012).

Today Paralympic prostheses have the 'c' or 'j' shape but depending on the manufacturer and their functionality they have slightly different shapes. However the concept of all of them is the same; running on the toes. Prostheses come in different range of stiffness which is based on the amputee's body weight. The results of some research indicate that adjusting the stiffness in the prosthesis can result in better symmetry in transtibial amputees (Gailey, 2003).

1.4 SPORT TECHNOLOGY INCLUSION DECIPLINE:

The field of study which surrounds debate with respect to the inclusion, actual acceptability or controversy of sport technology, has been termed human enhancement technologies (James, 2010), techno sport (Freeman 1991) or mechanical ergogenic (Holowchak 2002; Kyle 1991). Sport technology and performance enhancement can include material (Stoll et al. 2002; Froes, 1997) or chemical technologies (Savulescv et al. 2004; Miah 2005; Froes 1997) or artifact (Dyer 2010; Holowchak 2002). There are several case studies regarding to the sport technology inclusion which already have been adopted for use and have been the core of debates and discussions. Speedo speedsuit swimsuit, Ossur cheetah prosthesis, the Polara golf ball and Graeme Obree's "Old Faithful" bicycle are a few examples.

The decision regarding to viability or validity of a physical sport technology or equipment has to be resolved using ethical discourse. In fact there is a need for a defined framework for adoption of a particular sport technology based on an ethical foundation rather than an acceptance of an attitude to win at any cost (Freeman 1991). In order to determine the viability and the impact of sport technology inclusion, some quantitative methods have been used which included mathematical modelling (Haugen 2004), feasibility studies (Osborne 2005) and legal analysis (Zettler 2009; Shapiro 1991).

There are different scenarios and structured frameworks which consider the validity of inclusion of a particular sport technology in competitive sports. Gardner (1989) defines a four point framework to determine acceptability performance enhancement. According to this framework an enhancement would be considered inappropriate for use in sport if it causes:

- Harm
- Unnaturalness
- Coercion
- An unfair advantage

This scenario consider the result of technology inclusion rather than the actual intend behind technology's inclusion. The artificial legs are not natural product and they are essential to perform the act of running. Therefore this theory is too limited in its scope.

Miah (2005) expanded Gardner's framework to summarise several ethic attempts to structure ethical discourse. According to this scenario the technology should not be included at sports if;

- Technology that makes sport possible.
- Technology that affects safety and harm.
- Technology which de-skill or re-skill sport.
- Technology that dehumanises performance.
- Technology which affects participation.
- Technology that has a negative impact on sport.

This scenario is more comprehensive compared to Gardner's proposal. But it must be added that under this scenario the use of prosthesis technology would dehumanise sport.

Although different frameworks regarding to the inclusion of different types of prostheses have been legislated, but the use of carbon fibre prosthesis has been the core of attentions and many debates since its introduction. In 2005 bilateral amputee Oscar Pistorius was investigated due to the claim of having a mechanical advantage over able-bodied athletes (Dyer et al. 2010). In 2012, Allan Oliveira was criticised by Pistorius after 200m final for using the limbs that were alleged advantageous due to their length (Camporesi 2008).

There are many debates and discussions surrounding to the use of carbon fibre prosthesis in Paralympic Games which this thesis attempts to find some answers for them based on some statistical analyses. The main controversial issues in professional running activity in Paralympic Games can be summarized as:

1- A comparison over the performance of bilateral and unilateral amputees in Paralympic Games.
2- Considering the existing classification system (defined by IPC) in terms of fairness.
3- Identifying the major developments in the prosthesis design and a comparison in terms of performance before and after these technological developments (finding answers based on some statistical analyses).
4- A comparison between the performance of athletes in Paralympic and Olympic Games in running activity and identifying the major differences between these two sports events.

5- Providing a forecast for 2016 Paralympic Games in running activity, which will guide the decision makers that where the sport is going to.

Historical data at Paralympics Games has been considered as the source of information in order to answer these questions. These data are available in Paralympic website (www.paralympic.org) and are available within the public domain. In terms of analyses, ANOVA or Kruskal-Wallis tests has been used as the main statistical tools in order to clarify these controversial issues. However in the last chapter of this thesis some novel and complicated methods like Singular Spectrum Analyses (SSA) has been applied in order to provide a forecast and confidence interval for 2016 Paralympic Games.

CHAPTER 2: PARALYMPICS CLASSIFICATIONS IN RUNNING EXERCISE:

2.1 INTRODUCTION:

In Paralympics Games, in order to provide a fair competition for the athletes, they have been placed into different classifications. These classifications are created by the International Paralympic Committee (IPC) and have a root in the 2003 attempt to address the overall objective to produce a classification system which is equitable, accurate, reliable, consistent, credible and sport focused (IPC 2011). This chapter of the thesis, has an overview on the existing classifications for the lower limb sprinters, and attempts to see whether Paralympians in one specific classification have better performance compared to other existing classifications or not. In fact the results for T42 classification have been compared to T44, and it attempts to see whether the length of amputation can be considered as a factor which has some effect on the performance of athlete.

Also it tries to see whether current classifications in Paralympic Games are fair or not and it provides some recommendations for official bodies in Paralympic Games. As it was mentioned in the previous chapter, the bilateral amputees take advantage of symmetry in long running competition and in the current classification system in some cases bilateral and unilateral amputees have been placed into same group (T44 classification). This issue has been analysed from a statistical point of view and the last three Paralympic Games has been considered as the source of information in order to answer these doubts.

2.2 CLASSIFICATION SYSTEM:

In order to make disability sports as fair as possible, athletes should be grouped into different classifications based on extend and type of their disability (Bressan 2008). The term classification can be explained as a single group of unites or entities that are ordered into a number of smaller groups based on observable properties which they have in common (Tweedy & Vanlandewijck 2009). In the early stages of Paralympic Games the classification was undertaken as a specific designation of disability and it was based on a medical opinion of extent and the nature of disability (Dyer 2013). However the classification system has evolved and now is based on a functional assessment in order to determine which classification an athlete is placed into for their competition (Tweedy & Vanlandewijck 2009).

In this attitude a non-amputee who suffers from a similar impact of disability, can race alongside amputees because his impairment has a similar impact on performance (Bressan 2008). So the current classification system not only determines the eligibility to compete but also minimises the impact of the impairment on the outcome of the competition (Bressan 2008).

During the 1976-2012 timeframe the classification for running exercise in Paralympic Games changed consistently as the philosophy for classification was changed (Dyer 2013). The current classification system in Paralympic Games is based on a combination of letter and number in order to denote the events generalised context. As an example the letter can be T (meaning track) or F (meaning field based games). This is followed by a number which indicates the type of disability (Webster et al, 2001). In this system, as the number gets bigger, the severity of disability decreases (Bressan 2008).

If an amputee with a lower-limb amputation wishes to compete in running competition within the Paralympic Games, they are assessed for their physical functionality (Tweedy & Vanlandewijck 2009) and then allocated into one of three race classifications (IPC 2011). These amputee related racing classifications are defined as:

T42: a single (uni-lateral) above knee (trans-femoral) amputee or athlete with other impairments that is comparable to a single above knee amputation.

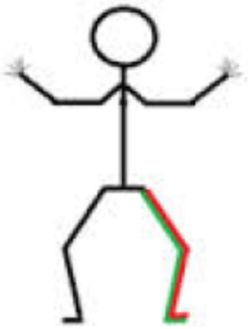

Figure 3: T42 Classification.

T43: double (bi-lateral) below knee (trans-tibial) amputees and other athletes with impairments that are comparable to a double below knee amputation.

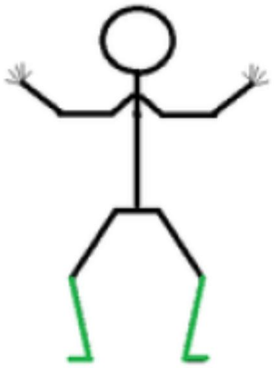

Figure 4: T43 Classification.

T44: an athlete with a below knee lower limb impairment/s that meets minimum disability criteria for: lower limb deficiency; impaired lower limb; impaired lower limb muscle power; or leg length difference.

Figure 5: T44 Classification.

It should be noted that in the analyses in this study, the T43 category were combined with the T44 category in the male running events. This was due to the governing body proposing that a low level of athlete participation in one or more classifications can lead to a combined classification in some events. Although less classifications for Paralympic Games make it easier to understand, but inaccurate or inequitable classifications can result in unfair competition (Jones & Howe 2005). The governing bodies in the Paralympic Games has introduced a minimum athlete participation level for each category, and in case where the participation is low, classifications can be grouped together.

2.3 DATA COLLECTION AND ANALYSIS:

The race results from the 100m and 200m form the basis of a statistical analysis of the 2012 (London), 2008 (Beijing) and the 2004 (Athens) Paralympics Games. The data are extracted from the official Paralympic website which are available within the public domain. It is worth to mention that, in 400m competition only athletes from T44 category compete against each other, so the data for 400m are not included in this part of thesis.

The aim of this chapter is to prove that from a statistical point of view, T44 classification has a better performance compared to T42. So in each case, the data has been put in two category (T44 or T42) and then ANOVA has been used as a statistical tool in order to identify the differences. In cases where the two conditions of normality and homogeneity of data have not been satisfied, instead of ANOVA, Kruskal-Wallis Test was used.

2.4 THE RESULTS:

Providing descriptive analyses for T42 and T44 classifications, can clarify the differences between the performances of athletes in these two groups. Table 1, compares the results of T42 and T44 in 100m and 200m competition.

Table 1: Descriptive data for T42 and T44.

Category	T42 Mean (s)	T44 Mean (s)
100m		
T42/Final-T44/Final	13.05	11.52
T42/All-T44/All	13.15	11.84
200m		
T42/Final-T44/Final	26.58	23.30
T42/all-T44/all	26.58	23.93

The results of Table 1 indicates that in all cases the mean completion time in T44 category is less than T42, which means T44 sprinters run faster than T42. But this is not a scientific approach in order to illustrate that results differ from each other significantly. In order to see whether Paralympians in running activity in different classifications have different level of performance, ANOVA Test has been applied. Table 2 represents the results of ANOVA Test (or Kruskal-Wallis Test where relevant). (H_0: T42 and T44 have the same results, H_1: T44 and T42 don't have the same results)

Table 2: Effect of classification**.**

Category	N	Homogeneity	Normality	Kruskal-Wallis
100m				
T42/Final-T44/Final	41(18,23)	0.443	0.260 , 0.038	6.06E-07
T42/All-T44/All	99(32,67)	0.365	0.000, 0.019	6.06E-07
200m				
T42/Final-T44/Final	37(15,22)	0.169	0.853 , 0.112	0.000 (ANOVA)
T42/all-T44/all	79(15,64)	0.177	0.853, 0.009	2.52E-07

The results of the Table 2 indicates that in both 100m and 200m competitions, there is a significant difference between T44 and T42 results in 95% confidence interval. This proves that the length of amputation is a factor which it does have considerable effects on the running activity.

2.5 THE SEPRATION OF T44 AND T43:

One of the most controversial issues in Paralympics Games in running activity is the separation of T44 and T43 in existing classification system. At the moment these two group compete against each other in one classification (Due to higher participation of unilateral amputees comparing to bilateral, it has been called T44). It has been quite well cited in many published works, that bilateral below knee amputees has some mechanical advantages comparing to unilateral amputees, due to the symmetry in their running activity (Noroozi et al. 2013). In chapter two it has been explained how symmetry in bilateral amputees can give them advantage in their running exercise. The results of this section can provide a good insight to this issue for the governing bodies in Paralympic Games in order to revise the existing classification system. This question has been answered with the help of some statistical tools.

2.5.1 DATA COLLECTION AND ANALYSES:

The results of next chapter, indicates that as the distance of the competition gets longer, bilateral amputees have an advantage comparing to unilateral amputees. Based on these findings, the results of 400m track event has been considered for analyses. The results of London 2012 and 2008 Beijing in 400m has been considered as the source of information in this section. Table 3 represents the descriptive analyses for the collected data.

Table 3: Descriptive analysis for T43 and T44.

Category	Sample size	Mean (s)	S.d
T43	11	50.86	2.57
T44	11	54.3	2.64

The descriptive analyses represented in Table 3, indicates that T43 classification has a better performance comparing to T44. However further analyses is required to see whether the results significantly differ from each other or not. In order to do so, ANOVA Test has been chosen as the statistical tool to answer this question. Table 4 illustrates the results of ANOVA Test and also the two key assumptions of this test (normality and homogeneity). (H_0: T43 and T44 have the same results, H_1: T44 and T43 don't have the same results)

Table 4: ANOVA Test for T43 and T44.

Category	Normality	Homogeneity	P value
T43 versus T44	0.567, 0.804	0.976	0.005

The results of Table 4 indicates that the results for T43 and T44 classifications, significantly differ from each other in 95% confidence interval. These results would lead decision makers in Paralympic Games to make these two groups separate from each other in the next Paralympic Games (which at the moment is not the case).

2.6 CONCLUSIONS:

In the Paralympic Games, athletes have been grouped into different classifications in order to make sports as fair as possible. Initially classification was based on a medical opinion of extend and the nature of disability but now the classification system is based on a functional assessment (Tweedy & Vanlandewijck 2009). So the current classification system not only determines the eligibility to compete but also minimises the impact of impairment on the results of competition (Dyer 2013).

The results of this thesis indicate that the athletes at T44 classification have a significantly better performance comparing to T42 classification. But it must be added that this is not in contradiction with the fairness of sport as they are competing in two separate groups. These results illustrate that whether the amputation has occurred from below or above knee, this could have considerable impact on the running activity. However analysing the performance of amputees within T44 category, indicated the fact that in this classification, bilateral and unilateral amputees have significantly different performance from each other. This is in contradiction with the spirit of sports and means that in this particular case, the classification system needs to be adjusted and these two groups (T44 and T43) must be separated into different track events. Based on these findings and considering Gardner's theory, putting T44 and T43 is against sports ethics, as it provides one group with an unfair advantage.

This chapter analysed the classification system at professional running in Paralympic Games in terms of fairness. However in order to answer the vital question that "whether Paralympic Games are fair or not?" further investigation is required. Another controversial issue regarding to this question, is affordability of buying professional prosthesis by athletes from all the nations who participate in this sports event (a sport with equal opportunities). Considering the legislation in terms of what type of prosthesis would be considered legal in Paralympic Games and also the price of prosthesis and how much they are affordable by all those who participate in Paralympics, would be two key issues which should clarified in order to evaluate the fairness of Paralympic Games at professional running.

CHAPTER 3: INDICATING THE DIFFERENCES BETWEEN BILATERAL AND UNILATERAL AMPUTEE’S PERFORMANCE IN RUNNING ACTIVITY

3.1 THE MECHANICAL DIFFERENCES BETWEEN RUNNING ON NATURAL FOOT OR PROSTHESIS:

It has been well cited in many published mechanical papers that, bilateral amputees in the running exercise take advantage of symmetry in their running activity comparing to unilateral amputees (Noroozi et al. 2013). This symmetry eventually results in less energy consumption by the athlete and less fatigue (Zetller 2009). However there has not been any published research which attempted to prove this idea from a mathematical point of view.

This chapter first introduces some experiments which were done in different organizations in order to compare the performance of lateral and bilateral amputees. Then the mechanical advantages of running on two blades comparing to only one blade has been introduced and it has been clarified how the symmetry in bilateral amputees can facilitate the running activity for them. Finally the hypothesis has been answered based on some statistical analyses.

The IAAF (International Association of Athletic Federation) intended to determine whether the famous blade running world record holder Oscar Pistorius Cheetah's (name of his blades) gave him an advantage over able-bodied competitors. In this study, the bio-mechanical and physiological performance of long sprint running by Pistorius were compared with five able-bodied athletes who were capable of similar levels of performance at 400m. The experiment included a 400m sprint, and the athletes used a mask in order to measure oxygen and carbon dioxide during inhalation and exhalation to test aerobic capacity, and ran on pressure plates to measure the force from blades and legs. The results of IAAF study indicated that Pistorius used 25% less energy in comparison to able-bodied athletes (Zetller 2009).

This research also reported that the amount of energy returned to Pistorius is three times higher than the energy attainable with a human ankle joint during maximum sprinting (Zetller 2009). The energy loss in Cheetah's was measured at 9.3% while the average energy loss in an ankle joint of able-bodied athletes was measured at 41.4% and the oxygen uptake for Pistorius was 25% lower than able bodied athletes (Zetller 2009). Lower oxygen uptake suggests lower exertion by the athlete and basically means the athlete is able to complete the task with a comparatively lower effort (Whaley 2006). Thus, it was concluded that there is a 30% mechanical advantage for blade runners in comparison to able-bodied athletes (Zetller 2009). It was also concluded that running with blades leads to less mechanical work for lifting the body combined with less vertical motion. Therefore, a blade runner can run in a flatter manner when compared with able-bodied athletes and benefit from what is termed as a bio-mechanical advantage (Zetller 2009; Hilvoorde et al. 2010). However, some other researches illustrate different results. The results of these researches represent higher metabolic costs (Czrniecki 1996; Genin et al. 2008; Waters et al. 1976), altered residual leg muscle activity (Fey et al, 2010) and reduced walking speed (Hermodsson et al. 1994; Perry et al. 1997; Powers et al. 1998; Robinson et al. 1997) for amputees when it has been compared to able-bodied people.

One of the key issues in a running competition is the limb repositioning time. The average male sprinter moves his leg from back to front in 0.37 seconds (Eveleth 2013). The five recent world record holders in 100m competition record the average of 0.34 seconds (Eveleth 2013). However, Pistorius swings his legs in 0.28 seconds, largely because his blades are lighter than a regular human leg. On average, his blade's weigh 2.4kg while natural feet weighs around 5.7kg (Eveleth 2013). In a study done by Noroozi et al. (2013) it was demonstrated that when a sinusoidal input with a frequency close to the natural frequency of an Energy Storing and Returning (ESR) foot is applied to a system, it can make the ESR foot susceptible to resonance which if sustained can lead to a bouncing or a trampoline effect. They also demonstrated theoretically that if this impulse can be synchronised with the frequency of human effort, it can result in storage or recovery of substantial amount of energy in the system (Noroozi et al. 2013).

In order to explain how this bouncing effect can occur, it could be added that in a prosthetic foot, when the excitation frequency (athlete muscle pressure) is increased, the inertia force will also increase until it reaches to a point at which the inertia force cancels the stiffness force of spring (Noroozi et al. 2013). In this situation the excitation force acts on the system without any resistance. This will result in oscillating of the mass at its natural frequency. In the absence of any damping, the amplitude of the resulting vibration will increase. This condition is called resonance. If the frequency is increased further, the inertia force will overcome stiffness force. The magnitude of oscillation will become small, until a point where the motion is controlled by the mass and then the system is said to be in isolation. In this situation the athlete must detect the Dynamic Elastic Response to Impulse Synchronization (DERIS) in order to maintain the steady state motion. In simple words, the athlete should apply an energy equal to the loss of energy in one cycle to maintain this advantage. For

Bilateral amputees this force is substantially less than for a normal foot due to the fact that residual energy is still in the mass and continually replenishes (Noroozi et al. 2013).
It can be identified that many researchers have considered the mechanical and biological differences between running on blades and on the natural foot, but none of them have considered this issue from a statistical point of view. In order to provide an answer for this hypothesis, two series of analyses have been applied. The first series of analyses has focused on the results of 2012 London Paralympic Games, and the second series has considered the last three Paralympic Games as the source of data. Although both analyses have the same procedure, after doing analysis on just the 2012 database, there was a concern that the sample size in some cases was not large enough. So in this case a larger database (last three Paralympic Games) has been considered in order to remove any doubts over the results.

3.2 DATA COLLECTION AND METHODOLOGY

The race results from the 100m, 200m and 400m competitions at 2012 (London), 2008 (Beijing) and the 2004 (Athens) Paralympics Games form the basis of the statistical analyses in this chapter. These results are located within the public domain and are extracted from the official website of the sport's governing body (Paralympic.org). This data includes the name, ranking, country of representation and the performance of each athlete. The number of prosthetic lower-limbs that each athlete may have, was derived from the athlete's biography and/or online photographic evidence. Appendix 1, represents the collected data for 2012 London Paralympic Games.

As the main purpose of this chapter is identifying the differences between three groups (bilateral, unilateral, and those who run on their natural leg but considered as amputee), the ANOVA test was identified as the best statistical tool to address this problem. ANOVA is used to find out how the average value of a numerical variable (called a dependent variable) varies across a set of conditions that have all been tested within the same experiment (Miller et al. 2006). ANOVA is a parametric test which assumes the normal distribution of the data (Guo, et al. 2013). The homogeneity test (whether different groups have the same level of variation between them or not) is another key assumption when using the ANOVA test (Zahayu et al. 2013). After creating the data sets for each research question, both normality and homogeneity tests were then undertaken. If both of these two key assumptions were satisfied *within* and *between* groups, the ANOVA test was then used in order to address each research hypotheses. If any of these assumptions were not then satisfied, the Kruskal-Wallis test was used instead of ANOVA. The Kruska-Wallis test is a non-parametric test which is not sensitive to normality (Guo et al. 2013).

3.3 THE RESULTS FOR 2012 LONDON:

Tables 5-7 present some descriptive statistics for 100m, 200m and 400m competitions. In these tables *N* stands for the number of competitors in each competition and the first number in parentheses indicates how many of them used two prosthetic feet, the middle number indicates how many of them used just one prosthetic foot, and finally the last one indicates how many did not use any prosthetic feet. For example, 6 (1,5,0) in the first row of Table 5 indicates that in T42/ 1st Round/ Heat 1, six athletes competed against each other while one of them used two blades, five of them used only one blade and none of them used their natural feet. Furthermore, *s.d stands* for standard deviation, Min and Max indicate the minimum and maximum of running time.

Table 5. Descriptive statistics for 100m competition.

Category	***N***	**Mean**	**Median**	***S.d***	**Min**	**Max**
T42/ 1st Round/ Heat 1	6(1,5,0)	13.73	13.07	1.55	12.43	15.76
T42/ 1st Round/ Heat 2	6(1,4,1)	12.92	12.73	0.49	12.53	13.77
T42/ Final	8(1,6,1)	12.71	12.69	0.25	12.4	13.03
T44/ 1st Round/ Heat 1	7(2,5,0)	11.92	12.16	0.55	11.08	12.49
T44/ 1st Round/ Heat 2	7(3,3,1)	12.61	11.92	0.5	11.18	12.61
T44/ 1st Round/ Heat 3	6(1,5,0)	11.96	12.61	0.56	11.29	12.69
T44/ Final	8(3,4,1)	11.24	11.19	0.32	10.9	11.97

Table 6. Descriptive statistics for 200m competition.

Category	***N***	**Mean**	**Median**	***S.d***	**Min**	**Max**
T42/ Final	9(2,6,1)	26.04	26.07	0.76	24.38	26.97
T44/ 1st Round/ Heat 1	6(3,3,0)	23.82	24.25	1.09	21.88	24.88
T44/ 1st Round/ Heat 2	6(1,5,0)	23.83	23.93	1.28	22.23	25.62
T44/ 1st Round/ Heat 3	6(1,4,1)	21.14	24.42	1.63	21.3	26.23
T44/ Final	8(3,5,0)	23.39	23.03	2.14	21.45	28.19

Table 7. Descriptive statistics for 400m competition.

Category	***N***	**Mean**	**Median**	***S.d***	**Min**	**Max**
T44/ 1st Round/ Heat 1	6(2,3,1)	55.01	55.35	3.09	50.63	59.79
T44/ 1st Round/ Heat 2	5(3,2,0)	51.87	52.29	2.22	48.31	53.86
T44/ Final	8(5,2,1)	51.9	51.62	2.93	46.68	55.91

So the data has been put into three groups. The first group the bilateral amputees, the second group the unilateral amputees and the third group who run on their natural leg but due to an impairment on their leg, they have been considered as disabled person and then they have been put on the right category. Table 8, represents the results for ANOVA or Kruskal-Wallis tests where relevant. The sing + indicates that the data at least in one of the subgroups in considered classifications is not normal. The sign – illustrates that homogeneity condition in some classifications has not been satisfied and the signs * and ** indicate significant level at 10% and 5% respectively. (H_0: number of blades does not make a difference in performance, H_1: number of blades make a difference in performance).

Table 8. ANOVA results for 100m, 200m and 400m competitions.

Category	**N**	***P-Value***
100m		
T42/1st Round/Heat 1-2	12 (2,9,1)+	0.656
T42/All	20 (3,15,2)+	0.354
T44/1st Round/Heat 1-3	20 (6,13,1)	0.667
T44/All	28 (9,17,2)+	0.922
200m		
T42/Final Round	9 (2,6,1) -	0.925
T44/1st Round/Heat 1-3	18 (5,12,1)	0.003**
T44/All	26 (8,17,1)+	0.009**
400m		
T44/1st Round/Heat 1-2	11 (5,5,1)	0.062*
T44/All	19 (10,7,2)	0.010**

The results of the ANOVA test confirms that there are no significant differences for the effect of disability status or using the number of blades, in all cases for 100m competition as the *P-Value*> 0.05. Similarly, the results indicate that there are no significant differences for 200m–T42. Note that, for 200m-T42 the sample size is too small ($N = 9$), and therefore it is difficult to discover a significant effect from the data as statistical tests require a larger N to guarantee a representative distribution of the population or groups of individuals to whom results will be concluded. Interestingly, and in contrast to the previous results, Table 8, reveals significant results for 200m T44 at a 5% significance level and for 400m T44 at a 10% significance level.

The results of this section indicates that as the length of the competition increases, the number of the blades which athletes use, can be considered as a factor which has a significant effect on the outcome of the competition. However, at the 100m competition this factor was not identified as an element which can impact the final results of the game. According to Gardner's theory and the findings of this chapter, the use of prosthetic foot gives an unfair advantage to the bilateral amputees and this is in contradiction with the sports ethics.

3.4 THE RESULTS FOR THE LAST THREE PARALYMPIC GAMES:

In order to increase the number of the data, in this section the results for 2012 London, 2008 Beijing and 2004 Athens has been mixed. The process of data collection and methodology in this section is exactly same as previous section and the descriptive analysis for Beijing 2008 and Athens 2004 Paralympic Games has been provided in Appendix 2.

The race-based data was categorized in three different groups. The first group comprises amputees who use just one prosthetic limb. The second group contains amputees who use two prosthetic limbs and the third comprises those who run without prosthetic limbs at all (but due to their functionality, compete in the same classification). In order to detect any differences in the mean completion time of the events, either the ANOVA or the Kruskal-Wallis tests were then applied. Table 9 represents the results of these tests. (H_0: number of blades does not make a difference in performance, H_1: number of blades make a difference in performance).

Table 9: The effect of number of blades (three Paralympics).

Category	**N**	**Homogeneity**	**Normality**	**Kruskal-Wallis**
100m-T42-all	31(3,25,3)	0.189	1.88E-05	0.478
100m-T44-all	66(13,49,4)	0.281	0.006, 0.251	0.064
200m-T42-All	15(2,11,2)	0.064	0.665	0.7892
200m-T44-All	64(14,47,3)	0.628	0.034, 0.000	0.002(ANOVA)
400m-T44-all	41(11,27,3)	0.7	0.804 , 0.406	0.0005(ANOVA)

In Table 9, the Kruskal-Wallis Test did not identify any significant difference regarding the effect of the number of blades with a 5% significance level in either the 100m or 200m. However, in the 400m and 200m T44 event, the test identified a significant difference between three groups at a 5% significance level. Alternatively, this finding could also be interpreted as when the distance of the competition gets longer (200m or 400m), the number of prostheses used ultimately affects the results of the event. In order to answer which group in particular has any advantage when compared to other groups, further analysis is required. In order to address this issue, the *Tukey Post Hoc* Test was applied. Post hoc analyses normally try to find some patterns and/or relationship between subgroups of sampled population that would otherwise remain undetected or undiscovered. The Tukey Post Hoc

Test provides a *P-Value* for each individual group when comparing to other sets of data. Table 10 and 11 represent the results of this test for 400m and 200m-T44 (as it was concluded that bilateral amputees have an advantage only in long run, so the results for 100m is not considered in this part).

Table 10: Tukey Post Hoc Test for 200m-T44.

Category		**Mean Difference**	**Std. Error**	**Sig.**
1 blade	2 blade	1.57312*	.38049	.000
	0 blade	-.02617	.74416	.999
2 blade	1 blade	-1.57312*	.38049	.000
	0 blade	-1.59929	.79504	.118
0 blade	1 blade	.02617	.74416	.999
	2 blade	1.59929	.79504	.118

As the sample size in the group possessing no prosthetic limbs is so small (2), we cannot make any robust conclusions and instead it can be focused on the results of the other groups. In Table 9 it is demonstrated that there is a statistically significant difference between the results of athletes who ran with 1 blade and 2 blades (P=.000). Based on the descriptive data for these two groups (22.7s for 2 blade and 24.27s for 1 blades), it is proposed that those who are bi-lateral lower-limb amputees have a competitive advantage compared to those who are uni-lateral. It is worth noting that although the normality test in this category was calculated as negative (and that we cannot use Post Hoc test in this case), but at least applying this test gives an indication as to where any difference is. Table 11 represents the results of Tukey Post Hoc Test for 400m competition.

Table 11: Tukey Post Hoc test for 400m.

Category		**Mean Difference**	**Std. Error**	**Sig.**
0 blade	1 blade	-.37667	1.35178	.958
	2 blade	3.27818	1.44676	.073
1 blade	0 blade	.37667	1.35178	.958
	2 blade	3.65485*	.79452	.000
2 blade	0 blade	-3.27818	1.44676	.073
	1 blade	-3.65485*	.79452	.000

The results of the Tukey Post Hoc Test indicate a statistically significant difference between the groups who use two blades when compared to other two groups. By considering the mean time of the race completion by these groups (50.86s for 2 prostheses, 54.51s for 1 prosthesis and 54.14s for no prosthesis) it is proposed that, when racing over 400m, runners who have used two prosthetic lower-limbs had an advantage compared to other groups who had only one (or none).

The results of this analysis supports the posed hypothesis and indicates that, from a statistical perspective, bi-lateral amputees participating in the Paralympic running events in either the 200m and the 400m distances, demonstrate better running performance when compared to unilateral amputees.

3.5 CONCLUSIONS:

There are different opinions regarding to the performance of amputees when it has been compared to able-bodied athletes from a mechanical point of view. While some researchers suggest lower exertion and a mechanical advantage for bilateral amputees compared to able-bodies athletes, some other researches represents higher metabolic costs, altered residual leg muscle activity and reduced walking speed for amputees. In chapter 5 of this thesis a comprehensive comparison over the performance of Paralympians and Olympians has been done. The results of this chapter represent a better performance for able-bodied athletes compared to amputees. The major differences between amputees and non-amputees in running activity can be attributed to the absence of ankle plantar flexor muscles, which provide needed body support , forward population and swing initiation during non-amputee running (Neptune et al. 2001).

The results of this chapter, supports the finding of the mechanical research that proves that bilateral amputees have an advantage in their running activity comparing to unilateral amputees. In fact running on two blades provides a good symmetry for the athlete and the internal forces in the system cancel out each other and the system goes into resonance which eventually can result in energy saving by the athlete (Noroozi et al. 2013). Result of the analyses in this thesis proves that as the distance of the competition gets longer, the bilateral amputees have an advantage to the unilateral amputees in running exercise. However it must be added that the tests applied into this chapter, did not detect any significant differences between the performance of bilateral and unilateral amputees in short distance competition (100m). In the starting block human ankle can generate much more energy comparing to prosthesis (Czerniecki 1991), but during the competition, bilateral amputees take advantage of what is called trampoline effect and help them to complete the game with lower exertion (Noroozi et al. 2013).

CHAPTER 4: THE IMPACT OF ESR FOOT IN SPORTS

4.1 INTRODUCTION:

During the history, prosthesis design has improved with the aim of replacing the missing anatomical part of body and eventually providing a life with better quality for the amputees. Over the last 30 years the improvements in prosthesis has resulted in a better performance by the amputees. It has been quite well sited in many published papers, that the introduction of Energy Storage and Return foot (ESR) has made a breakthrough in the design of prosthesis (Nolan 2008). Over the last few decades along with the development of carbon fiber prosthesis, amputee sport performance has greatly improved (Nolan 2008). As the margins between winning and losing have become smaller, athletes increasingly have been relying on the prosthesis technology in order to give them an advantage over other athletes and break existing records (Nolan 2008).

In chapter 1, it was mentioned that introduction of ESR foot has a revolutionary impact on running performance by the amputees. In that chapter, the mechanical advantages of running with ESR was introduced when it was compared to classic prosthesis. Although many factors can contribute to the performance enhancement in prosthesis, but the concept of storing energy and returning it to the body, was the major development in the design of prosthesis. Figures 6 and 7 provide a demonstration of a modern version of classic prosthesis (SACH) and the Cheetah which is a developed form of ESR foot.

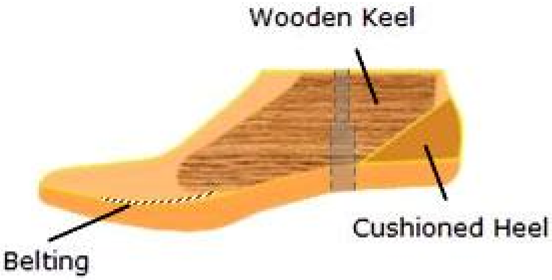

Figure 6: SACH foot (www.oandp.org)

Figure 7: Flex-Foot Cheetah (www.ossur.com)

This chapter attempts to prove that ESR foot made a significant difference in running exercise from the statistical point of view. ESR first was used in 1988 Paralympic Games by a number of athletes (Pailler et al. 2004). However in 1992 the heel was removed from ESR and the concept of running on toe was introduced (Pailler 2004). So the data after 1992 has been considered as running by ESR and any data prior to this date was considered as running by classic prosthesis. The next chapter clarifies the process of data collection.

4.2 DATA COLLECTION:

Tables 12 and 13 represent the above and below knee podium results only for 100m Paralympic games after 1984. Results prior to 1984 are hard to come by as the classification system was changed frequently and the record keeping by the IPC was poor. The official website of Paralympic Games has been the source of information in data collection.

Table 12: Below knee 100m podium.

100m Male	**1st**	**Time**	**2nd**	**Time**	**3rd**	**Time**
1984, New York/S.M.	Suchocki, Kazimierz	13.12	Johann, Jurgen	13.82	Egan, Joseph	13.92
1988, Seoul	Oehler, Dennis	11.73	Lowe, Adrian	12.37	Barrett, Robert	13
1992, Barcelona	Volpentest, Tony	11.63	Oehler, Dennis	12.38	Fuller, Neil	12.55
1996, Atlanta	Volpentest, Tony	11.36	Fuller, Neil	11.97	Thomas, Bradley	12.02
2000, Sydney	Shirley, Marlon	11.09	Frasure, Brian	11.46	Fuller, Neil	11.65
2004, Athens	Shirley, Marlon	11.08	Frasure, Brian	11.11	Pistorius, Oscar	11.16
2008, Beijing	Pistorius, Oscar	11.17	Singleton, Jerome	11.2	Frasure, Brian	11.5
2012, London	Peacock, Jonnie	10.9	Browne, Richard	11.03	Fourie, Arnu	11.08

Table 13: Above knee podium 100m.

100m Male	**1st**	**Time**	**2nd**	**Time**	**3rd**	**Time**
1984, New York/S.M.	Martinson, Jim	17.13	Lenzo, Kris	17.58	O'Rourke, Gerry	17.62
1988, Seoul	Schaffhauser, Todd	15.77	McGregor, Kerrod	15.98	Siegl, Andreas	16.95
1992, Barcelona	Gaetani, Joe	12.23	Christen, Lukas	13.62	Belitz, Gunther	15.75
1996, Atlanta	Christen, Lukas	13.55	Gregori, Paul	14.05	Schaffhauser, Todd	14.6
2000, Sydney	Connor, Earle	12.61	Christen, Lukas	12.98	Danylov, Andriy	13.28
2004, Athens	Czyz, Wojtek	12.51	Kayitare, Clavel	12.78	Popow, Heinrich	13
2008, Beijing	Connor, Earle	12.32	Popow, Heinrich	12.98	McFall, John	13.08
2012, London	Popow, Heinrich	12.4	Reardon, Scott	12.43	Czyz, Wojtek	12.52

Energy Storage and Return foot (ESR) was introduced in 1988 in elite sports (Pailler et al. 2004). But it has been used by all the athletes in Paralympic Games after 1992(Pailler et al. 2004). Here the aim is to prove that the introduction of ESR foot facilitated the running activity for Paralympians.

In order to answer this question, the data can be categorized into two separate groups. In the first group the data for 1984 and 1988 (when athletes used classic prosthetic feet in Paralympics) and in the second group data since 1992 (when all the athletes in Paralympic games started using ESR) were considered. In order to have a better insight into the data, some descriptive analyses has been provided. Tables 14 and 15 represent some descriptive analyses for the data.

Table 14: Descriptive data for below knee 100m.

Category	**Number of Data**	**Mean (s)**	**Standard deviation**	**Min (s)**	**Max (s)**
Before ESR	6	12.99	0.84	11.73	13.92
After ESR	18	11.46	0.48	10.9	12.55

Table 15: Descriptive data for above knee 100m.

Category	Number of Data	Mean (s)	S.d	Min(s)	Max(s)
Before ESR	6	16.84	0.79	15.77	17.62
After ESR	18	13.15	0.91	12.23	15.75

It is worth to mention that before 1988 races over 200m hardly took place due to the low participation. Also for 400m Paralympic Games before 1988 there is no available data for the same reason. So 100m has been considered as the only data base which can be applied in order to see the impact of ESR in elite sports.

4.3 METHODOLOGY AND ANALYSIS:

As the aim is identifying the differences between two groups, the ANOVA test can be a good statistical tool in order to answer this question. However, normality and homogeity within and between groups are the two key assumptions in ANOVA Test which has to be satisfied (Gue et al. 2013; Zahayu et al. 2013). However it is needed to acknowledge a limitation in this method as the analyses of this part of the thesis have not differentiated between different amputations (uni/bilateral). This has been mainly due to the poor record keeping by the governing bodies and also the constant change of classification system.

By considering the data after 1992, it can be realized that some athletes have participated in more than one Paralympic Games. As the data in some cases are related to one person, and their characteristics (especially on mentality features) does not change, so the data cannot be considered independent from each other and the problem of repeated measure has to be addressed.

In order to solve this problem, an average has been taken over the data related to those athletes who participated in more than one race. By doing so, all the numbers in the process of data analysis, will be considered totally independent from each other. For example in Table 12, the athlete “Volpentest, Tony” was participated in 1992 and 1996 Paralympic Games. In order to have one unique number for this athlete, an average over these two data had been taken, and this average was used in data analysis.

Table 16 represents the *P-Value* of normality and homogeneity and ANOVA (or Kruskal-Wallis Test). Whenever the assumptions for ANOVA Test were not satisfied (normality and homogeneity), Kruskal-Wallis Test was used. Kruskal-wallis Test is a non-parametric test which is not sensitive to normality (Guo et al. 2013). In Table 16, the numbers in parenthesis in the second column, represents the number of data which the analyses have been applied to. For example in Table 16, numbers 6 and 11 in parenthesis in second column, illustrate that before the introduction of ESR 6 data have been available and after introduction of ESR 12 independent data has been used in the process of data analysis. (H_0: ESR and classic prosthesis have the same results, H_1: ESR and classic prosthesis don’t have the same results).

Table 16: Effect of ESR (averaging).

Category	Normality	Homogeneity	Kruskal-Wallis
Below Knee	0.666 (6), 0.057 (11)	0.374	0.000(ANOVA)
Above Knee	0.237 (6), 0.0443 (12)	0.866	0.000

The results in Table 16 indicate that, the test has identified a significant difference between groups in 95 % confidence interval (for both below and above knee). These results prove that the application of the ESR foot in Paralympic Games, has facilitated the running activity for the athletes. These findings show that how technology inclusion can make a difference in the results of a competition and how it can improve the quality of life for amputees.

However during the research, some of the experts had a different opinion considering the independence of the data for those athletes who participated in more than one Paralympics. After consulting this issue with some experts, it was decided to do analyses again based on considering all the data independent from each other as well (no averaging). Paralympic Games happen at four yearly intervals at set dates in different geographical locations.

Athletes competing in more than one Paralympic Games will be at a different point of age and physiological development.
Although we have some data which are generated by only one person in tables 12 and 13, but they have been gained in a totally different situation from each other. That means all of the data in Tables 12 and 13 can be considered independent from each other and no averaging over the data is needed.

Mentality of an athlete may not change over the years (ambitious to be the champion and planning their life based on this goal), but their physical ability does change. Muscle mass typically degrade from the age of 30. The state of the ability changes constantly and without knowing the age of athlete, it is difficult to know in what stage of physical development they are in. In this regards Paralympic Games are unique because the Paralympians are often older and of greater varying standard than the able-bodied equivalent at the Olympics.

In addition, athlete's running style (skill acquisition) might evolve over time too. In the case of this data it is not known if the athlete changed his perception of prosthesis over time and this may have some bearing on whether their running style has change over time too. For example, "Oscar Pistorius" has a different running strategy to what he used to have (fast start, slow finish or slow start and fast finish). This is not merely due to his change in physiology but also on the perception (i.e. stiffness) of prosthesis he choose to use. The stiffness of the limb will change the way an athlete can run, as the stiffness can be affected by the prosthesis material and the limb length. Table 17 represents the result of analysis based on considering all the data in Tables 12 and 13, independent from each other. The results of Table 17 indicates that in 95% confidence interval, there is a significant difference between groups (in both cases of below and above knee). (H_0: ESR and classic prosthesis have the same results, H_1: ESR and classic prosthesis don't have the same results).

Table 17: Effect of ESR (independent).

Category	Normality	Homogeneity	Kruskal-Wallis
Below Knee	0.666 (6), 0.019 (18)	0.285	0.001
Above Knee	0.237 (6), 0.005 (18)	0.860	0.000

So regarding to the independence of the data, two ideas where introduced. In the first one an averaging over the repeated measure was taken, while in the second one all the available data has been considered independent from each other, and changing in the physiology of the body by the time, and change in the design of the prosthesis were introduced as the main reasons in second part of analysis. Tables 16 and 17 illustrate that both approaches has the same results and they confirm that by introduction of the ESR foot the Paralympians achieved a significantly better results.

4.4 CONCLUSIONS:

The early models of prostheses in professional sport produced the minimum amount of energy storage and return during the stance phase (Ehara et al 1993) due to their limited deflection and high stiffness. In order to address these problems, ESR foot has been developed which stores and releases elastic energy during stance phase (Hafner et al. 2002) and provides forward propulsion and leg swing initiation and body support (Zmitrewicz et al. 2007).

With the recent developments of carbon fibre running specific prostheses, individuals with lower extremity amputation are regaining the functional capability of running (Nolan 2008). Current running specific prostheses are made from carbon fibre, which generates high frequency vibration when used (Lehmann et al. 1993). By introducing of the ESR foot the concept of energy storage and return it as a kinematic form of energy, opened the new doors for prosthetic design. The results of this chapter proves that ESR foot made a significant change in running activity for Paralympians. By considering the descriptive analysis provided in this chapter, it can be concluded that, sprinters in Paralympic Games run faster after introduction of ESR foot.

It should be added that regarding to the independence of data set in this chapter, two different hypotheses were introduced. The first one considered an averaging over the repeated measure while the second hypothesis considered all the available data independent from each other. In both cases the results of the tests were the same, and the tests detected a significant difference after introduction of ESR foot in Paralympic results. In the other words, ESR foot facilitated running activity for amputees and enhanced their performance in competitive sport.

CHAPTER 5: OLYMPICS VERSUS PARALYMPICS

5.1 INTRODUCTION:

This chapter attempts to provide a comparison between Olympics and Paralympic Games in running activity. The aims and objectives in this chapter can be summarized as:

- Summarizing all the historical data in running activity at Olympics and Paralympic Games into some tables and graphs which can provide a representation of the performance of the athletes in these two sports events.
- Running a series of statistical analysis in order to see whether there is any significant different between the results of Olympic and Paralympic Games in running activity

5.2 DATA COLLECTION AND ANALYSES:

In order to provide some answers to the raised questions in the previous section, the podium of Paralympic and Olympic results for running activity since 1984 has been extracted. The official website of Olympic and Paralympic Games has been the source in order to collect these data (www.paralympic.org; www.olympic.org). The process of data collection and data analysis has been limited only to the 100m track event, as the decent amount of data for Paralympic Games for races of 200m or over has not been available. The podium results for Paralympic Games has been indicated in Tables 12 and 13 from previous chapter. Table 18 represents the podium results for 100m Olympic Games.

Table 18: Podium for Olympics 100m.

100m Male	1st	Time	2nd	Time	3rd	Time
1984, New York/S.M.	Carl LEWIS	9.99	Sam GRADDY	10.19	Ben JOHNSON	10.22
1988, Seoul	Carl LEWIS	9.92	Linford CHRISTIE	9.97	Calvin SMITH	9.99
1992, Barcelona	Linford CHRISTIE	9.96	Frank FREDERICKS	10.02	Dennis MITCHELL	10.04
1996, Atlanta	Donovan BAILEY	9.84	Frank FREDERICKS	9.89	Ato BOLDON	9.9
2000, Sydney	Maurice GREENE	9.87	Ato BOLDON	9.99	Obadele THOMPSON	10.04
2004, Athens	Justin GATLIN	9.85	Francis OBIKWELU	9.86	Maurice GREENE	9.87
2008, Beijing	Usain BOLT	9.69	Richard THOMPSON	9.89	Walter DIX	9.91
2012, London	Usain BOLT	9.63	Yohan BLAKE	9.75	Justin GATLIN	9.79

Athletes in Paralympics Games compete against each other with different level of amputation. So they have been put into different categories in order to provide a fair competition. So the data in Paralympic Games has been divided into below and above knee amputees.

Table 19 represents the average of podium Olympics and Paralympics (for both below and above knee) and also the differences between these two games in seconds for 100m competition.

Table 19: Average podium for Olympic and Paralympic 100m.

Year	Olympic (s)	Paralympic (s)	Difference (s)
1984	10.13	15.53	5.40
1988	9.96	14.3	4.34
1992	10.01	13.03	3.02
1996	9.88	12.93	3.05
2000	9.97	12.18	2.21
2004	9.86	11.94	2.08
2008	9.83	12.04	2.21
2012	9.72	11.74	2.02

Figure 8, provides a better representation of data provided in Table 17.

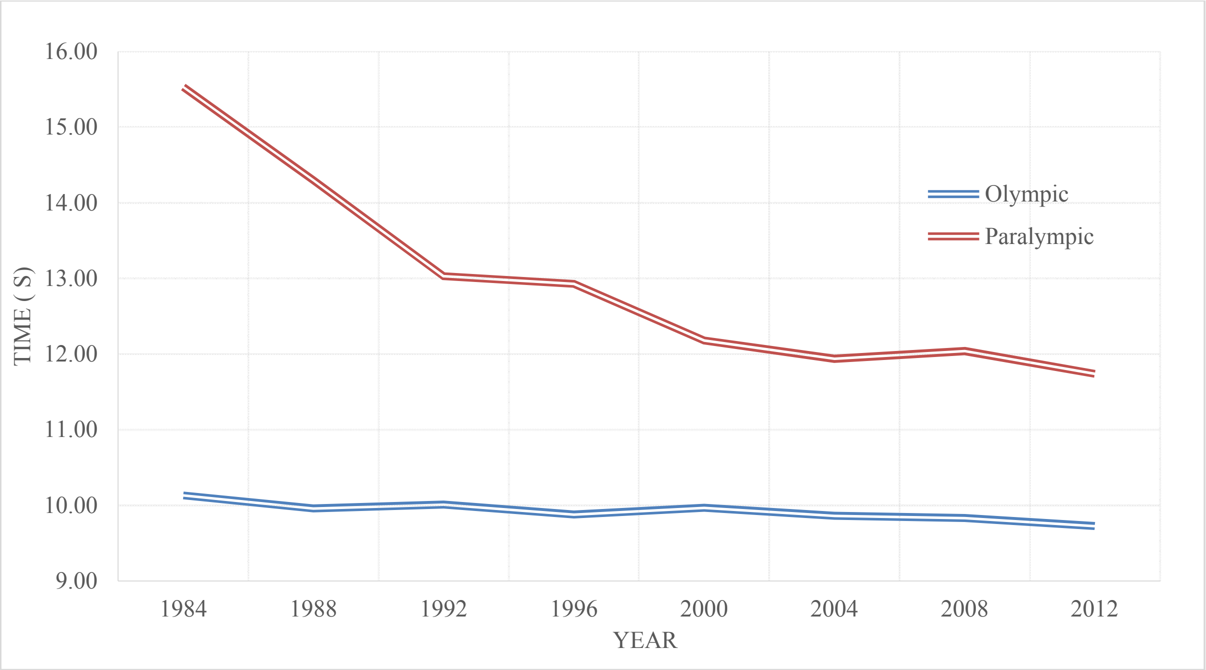

Figure 8: Average podium for Olympic and Paralympic 100m.

Figure 8 illustrates that while Olympic results has had a steady decrease since 1984, Paralympic results has had a sharp decrease (specially between 1984 till 1992) over the same period of time. Table 18 provides some descriptive analysis for the information included in Table 19.

Table 20: Descriptive analysis for Olympic and Paralympic results for 100m.

Category	**Number of Data**	**Mean (s)**	**S.d**	**Min**	**Max**
Olympic	8	9.92	0.12	9.72	10.13
Paralympic	8	12.96	1.33	11.74	15.53

In Table 20, S.d stands for standard deviation, Min stands for minimum and Max stands for maximum.

Another way of illustrating the differences between results of Paralympic Games and Olympic, is introducing another numeric parameter which is called Performance Improvement Index (PII). This index provides the percentage increase of a performance from one Paralympic Game to the next. This could be expressed as:

$$\text{Performance Improvement Index} = [1 - (\frac{t_2}{t_1})] \times 100$$

In this formula, t_1 is the first performance and t_2 is the subsequent performance. The results of this index has been represented as a percentage.

Table 21, compares the performance improvement index for Paralympic and Olympic Games.

Table 21: Performance Improvement from prior game.

Year	**Paralympic PII from Prior game**	**Olympic PII from Prior game**
1984	n/a	n/a
1988	7.92	1.71
1992	8.88	-0.47
1996	0.77	1.30
2000	5.80	-0.91
2004	1.97	1.07
2008	-0.84	0.30
2012	2.49	1.09

Table 21 illustrates bigger PII for Paralympic companying to Olympic Games. Also Table 20, represents a big level of variation inside of the historical data for Paralympics companying to Olympics (bigger standard deviation). All of these arguments means that Paralympic Games has faced a bigger level of change comparing to Olympic Games. This issue could be due to several reasons. The most important ones can be stated as:

- Amputee running is in a state of relative infancy. This is the case both in terms of athleticism and equipment (especially in 80's and 90's). It has to be considered Olympic running has taken place since 1896 and amputee competitive running only since 1976 (Dyer 2013). This will make quite a big difference in sports development.

- The level of disability and the athlete experience at running with equipment will make a big difference between two athletes. Although athletes in Paralympic Games have been put into different classifications in order to provide a fair competition, it needs to be considered that even a few inches difference in amputation length from one amputee to another is going to affect their ability to run.

- Introduction of Energy Storage and Return foot (ESR), facilitated the running activity for amputees. ESR has been made with lighter material comparing to the classic prosthesis, and also energy returned from prosthesis to body during the "stance phase" of running activity is bigger in ESR comparing to classic prosthesis (Nolan 2008). That means application of ESR foot in elite sports, resulted in better performance for amputees.

- The level of participation potentially can affect the results and also the level of the variation in final records. By considering the historical data it can be realised that the number of competing athletes at Paralympic Games peaked in 1984 and then a sharp decline in 1988. There is a gradual minor peak in 1996, then a gentle decline until the biggest increase since 1984 in London 2012 (Dyer 2013). However it must be included, that the results of a study indicates that technological change is more responsible for increased performance, rather than widening participation (Munasinghe 2001). Results of another study indicates that increases in the global population will not impact on athlete performance (Foster et al. 2010).

All of the stated analyses and discussions so far provide a good comparison between the overall Paralympic and Olympic results. It will be interesting to provide some comparison between these two events after all of the developments in sports technology and to see how the recent figures has changed. In order to do so, London 2012, has considered at the main data base in order to represent the differences between Olympians and Paralympians. It has been proven that amputees in T44 has a better performance comparison to T42, and also as the distance of the competition gets longer, bilateral amputees has an advantage comparing to unilateral amputees as they take advantage of symmetry during their running activity. So comparing the results in track 400m for amputees who participated in T44 (London 2012) to the same track in Olympic, can illustrates where the gap between these two events can be minimized.

Table 22, indicates the results of final round, T44 classification for 400m Track events, for London 2012, men Paralympic games. The column with the title “Specification” indicates the number of prosthesis foot which athletes were wearing during competition. Table 23, illustrates the results of final round, men, 400m Olympic Games

Table 22: T44, 400m, Final round, London 2012 (men) Paralympic.

Rank	**Athlete**	**Time(s)**	**Country**	**Specification**
1	Pistorius, Oscar	46.68	RSA	2 leg
2	Leeper, Blake	50.14	USA	2 leg
3	Prince, David	50.61	USA	1 leg
4	Oliveira, Alan Fonteles Cardoso	51.59	BRA	2 leg
5	Behre, David	51.65	GER	2 leg
6	Wallace, Jarryd	53.9	USA	1 leg
7	Prokopyev, Ivan	54.74	RUS	2 leg
8	Liu, Zhiming	55.91	CHN	0 leg

Table 23: 400m Olympic men final round.

Ranking	**Name**	**Country**	**Time (s)**
1	Luguelin SANTOS	DOM	44.46
2	Lalonde GORDON	TTO	44.52
3	Chris BROWN	BAH	44.79
4	Kevin BORLEE	BEL	44.81
5	Jonathan BORLEE	BEL	44.83
6	Demetrius PINDER	BAH	44.98
7	Steven SOLOMON	AUS	45.14

Table 24, provides some descriptive analyses in order to provide a better comparison between the results (S.d stands for standard deviation). Figure 9, provides a good indication of the results.

Table 24: descriptive analysis for 400m Olympic Vs Paralympic.

Category	**Number of Data**	**Mean(s)**	**S.d**	**Min (s)**	**Max(s)**
Olympic	7	44.79	0.24	44.46	45.14
Paralympic	8	51.90	2.94	46.68	55.91

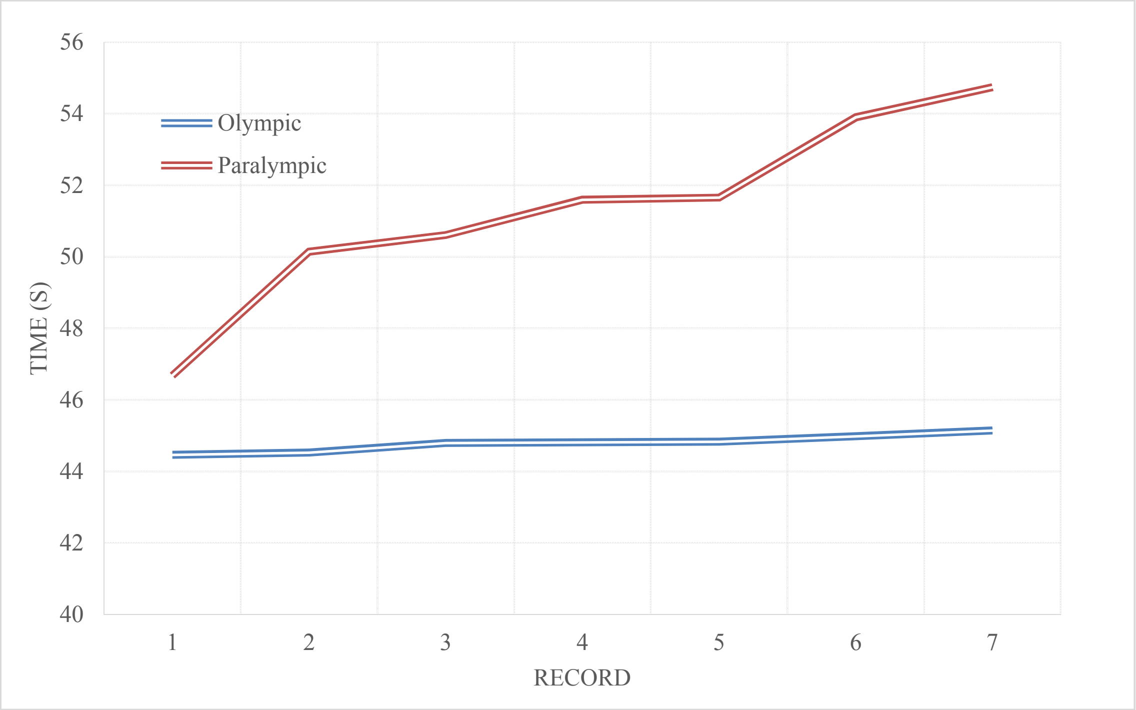

Figure 9: 400m Olympics VS Paralympics.

As comparing simply the mean for two populations is not a scientific approach in order to identify differences between two groups, further analysis is required in order to represent the differences. After considering the normality and homogeneity of data in each groups, ANOVA test has been applied to data in order to see whether the test detect any difference between two groups or not. Table 25, indicates that the data in both groups has been distributed normally, but the level of variation between two groups differ from each other (*P-Value* of third column) due to all the reasons which has been mentioned already.

Table 25: 400m Comparison between Olympic and Paralympic.

Comparison	Normality	Homogeneity	P value
Olympic VS Paralympic	0.681, 0.833	0.020	0.001

Considering that 5 athlete out of 8 in Table 22 are bilateral amputees (and take advantage of symmetry in long run) and all data in this table belongs to T44 category (and they have better performance comparing to T42), it can be concluded that this is the best point where the gap between Olympics and Paralympic gets minimized. Analyses in this chapter started from a point which the differences between Olympic and Paralympic were maximum, and finally it reached to a point where the gap minimized. However, the results of Table 25, indicate that after all developments in the design of prosthesis, and also considering the best track event which amputees have better performance comparing to other groups in Paralympic Games, Still test detected a significant difference in 95% confidence interval.

5.3 CONCLUSIONS:

Considering the available historical data at Olympic and Paralympic Games, it could be identified that at the early years of introduction of Paralympic Games, there was a big gap between the results of these two sports event at running exercise. But by the time, this gap has become smaller. These improvements at the Paralympics results mainly has been due to technological developments in prosthesis design and increased level of participation. This chapter introduces T44/400m/ London 2012 track event as the point where the gap between Olympics and Paralympics can get minimised due to several reasons:

- It was proved that T44 classification has a better performance compared to T42.
- Technological improvement can represent its impact on running exercise (2012).
- It was proved that as the distance of the competition gets longer (400m), bilateral amputees take advantage of symmetry and can complete the competition with lower exertion.

The results of this chapter proves that even at this track event, still Paralympians have a lower performance comparing to Olympians. This is due to the fact that human ankle can generate substantially more work than any other joint in the lower limb (Nolan 2008). Although technological developments have resulted in improved energy efficiency in prostheses, but still they are unable to provide anywhere near to the range of that of the human foot (Nolan 2008).

The results of this chapter indicate higher level of variation in the Paralympics results compared to Olympics. Two numeric parameters of standard deviation and PII were introduced as the tools to calculate the level of variation. Infancy of Paralympic Games, different level of amputation in the participants and the impact of the technology at the sports for disabled people, were introduced as the main reasons which justify this high level of variation in the Paralympics results.

CHAPTER 6: A FORECAST FOR 2016 PARALYMPIC IN RUNNING EXERCISE

6.1 INTRODUCTION:

Providing a forecast for sports will provide governing bodies with some valuable information which will give them an insight into where the sports is going to in the future. Decision makers by evaluating the results can revise or improve their plans in the future of sports. Regarding to the technology enhancement, amputees are achieving better records by the time. Proving a forecast can represent the fact that, how the results of the competition for amputees can get close to the results of non-amputees in the future. This will be effective in changing the people's perception towards disability.

There are diverse methods for forecasting based on the historical data. Between all of them, Singular Spectrum Analysis (SSA) is a novel and sophisticated approach which works better comparing to the other method (like MA, ARMA, and ARIMA) (Hassani 2007), and also it can be applied when just a limited number of data are available (Hassani & Zhigljavsky 2009; Hassani 2007).

SSA was introduced with the publication of some papers by Broomhead (e.g Broomhead & king 1896) while it was independently developed in Russia (St. Petersburg, Moscow) and in several groups in the UK and USA (Hassani 2007). SSA can be applied in many fields of research including: mathematics, physics, economic and financial mathematics, meterology and oceanology, social science and market research (Hassani 2007). SSA is a very useful tool which can be used for solving many problems including: trend extraction, smoothing, extraction of seasonality components, simultaneous extraction of cycles with small and large periods, finding structure in short time series, change point detection and extraction of periodicities with varying amplitude (Hassani 2007).

This chapter attempts to provide a forecast for lower limb amputees for 100m in 2016 Paralympic Games based on the singular spectrum analysis. First the process of data collection has been explained and then an introduction to SSA has been provided and all the steps in this approach has been introduced and explained and eventually from the available historical data some conclusions has been drawn based on the output of Caterpillar SSA software.

6.2 DATA COLLECTION:

In order to provide a forecast for 2016 Paralympic Games, first it is needed to build a time series based on the historical data. In order to do so, the podium for 100m lower limb amputees (above and below knee) has been extracted from the official website of Paralympic Games for the last 8 Paralympic games (from 1984 New York, till 2012 London). These data has been already represented in Tables 10 and 11. It should be mentioned that historical data for 200m races or over before 1992 has not been available. First of all races over 200m hardly took place due to the low level of participation in that time and secondly in some cases the data has not been available due to the poor record keeping system of IPC over this period. So the focus of data analysis process in this chapter has been put on only the 100m data.

Considering only the podium results, provide more reliable output in data analysis as it would omit the outliers in the process of data collection.

In order to build the time series it is needed to have one unique number for each year. So the average of podium has been considered for each year. Tables 26 and 27 represent the average of podium in Paralympic Games 100m for below and above knee amputees.

Table 26: Mean podium for below knee 100m.

Year	Paralympic (s)
1984, New York/S.M.	13.62
1988, Seoul	12.37
1992, Barcelona	12.19
1996, Atlanta	11.78
2000, Sydney	11.40
2004, Athens	11.12
2008, Beijing	11.29
2012, London	11.00

Table 27: Mean podium for above knee 100m.

Year	Paralympic (s)
1984, New York/S.M.	17.44
1988, Seoul	16.23
1992, Barcelona	13.87
1996, Atlanta	14.07
2000, Sydney	12.96
2004, Athens	12.76
2008, Beijing	12.79
2012, London	12.45

Tables 26 and 27 summarize all the information of Tables 12 and 13 into a unique number for each Paralympics Game, which can be considered as a time series. Singular Spectrum Analysis can be applied into this time series in order to provide a forecast for 2016. But before providing the output of the SSA, it is worthwhile to introduce all different steps and elements of SSA. Next section provides a comprehensive explanation for Singular Spectrum Analysis.

6.3 BACKGROUND:

Before introducing SSA methodology and data analysis, it worth to explain some of the key concepts which are used in SSA in order to provide a better understanding for those who are not familiar with this technique.

Identity matrix: Identity matrix is a square matrix with entries on the diagonal are equal to 1.

Transpose: The transpose of a matrix is created by converting its rows into columns.

Diagonal matrix: In a Diagonal matrix all the values are zero except the values run along with main from the upper left corner to the lower right corner.

Orthogonal matrix: Matrix **A** is orthogonal if $\mathbf{A} \times \mathbf{A}^{\mathbf{T}} = \mathbf{A}^{\mathbf{T}} \times \mathbf{A} = \mathbf{I}$.

Eigenvectors and Eigenvalues: If consider A as a matrix, an Eigenvector is a nonzero vector that satisfies the equation: $A\vec{v} = \lambda\vec{v}$

In this equation, **A** is a square matrix, λ is a scalar and it is called eigenvalue and v is the eigenvector. So by treating the matrix as a system of linear relationship we can find the eigenvalues and corresponding eigenvectors.

Singular value decomposition (SVD): SVD is based on a theory from linear algebra which says a rectangular matrix can be broken down into three matrixes, an orthogonal matrix **U**, a diagonal matrix **S** and the transpose of an orthogonal matrix **V**. The equation below is a representation of this theory:

$$\boldsymbol{A}_{mn} = \boldsymbol{U}_{mm}\; S_{mn}\, \boldsymbol{V}_{nn}^{T}$$

In this equation, $\mathbf{U}^T \mathbf{U} = I$, $\mathbf{V}^T\mathbf{V} = \mathbf{I}$; the columns of U are orthonormal eigenvectors of $\mathbf{AA}^T$, the columns of V are orthonormal eigenvectors $\mathbf{A}^T \mathbf{A}$, and **S** is a diagonal matrix containing the square roots of eigenvalues from **U** or **V** in descending order.

6.4 METHODOLOGY:

In SSA the main purpose is decomposing the original series into a sum of series, so that each component in this sum can be considered as either a trend, periodic or quasi-periodic component or noise. This is followed by the reconstruction of the original time series.

This technique is consisted of two complementary stages: decomposition and reconstruction. Each of these stages includes two separate steps. SSA in the first stage decomposes the series and in the second stage reconstructs the original series. The reconstructed series (which are without noise) can be used for forecasting the new data point. In the next part, each of these four steps are explained in more details.

6.4.1 DECOMPOSITION:

This stage of singular spectrum analysis can be separated into two subgroups: embedding and singular value decomposition.

6.4.1.1 EMBEDDING:

Embedding can be considered as a mapping that transfers a one-dimensional time series

$Y_T = (y_1, \ldots, y_T)$ into the multi-dimensional series X_1 ,…….., X_K with vectors

X_i = (y_i, . . . , y_{i+L-1}) $\in \mathbf{R}^L$, where K= T-L+1 (Hassani 2009). Vectors X_i are called lagged vectors. The only parameter of embedding step is window length (L) which is an integer such that 2≤ L ≤T. The results of this step is the trajectory matrix **X** = [X_1, . . . , X_K] = $(x_{ij})_{i.j=1}^{L,K}$. Trajectory matrix **X** is a Hankel matrix, which means that all the elements along the diagonal *i+j = const* are equal (Hassani 2007).

As the window length is the only parameter in embedding section, knowing that the time series may have a periodic component with an integer period, in order to achieve a better separability of this periodic component it is advisable to take the window length proportional to that period (Hassani 2007).

6.4.1.2 SINGULASR VALUE DECOMPOSITION (SVD):

After making trajectory matrix, SVD will be applied to create the singular value decomposition of the trajectory matrix and represent it as a sum of rank-one bi-orthogonal elementary matrices (Hassani 2009). In fact in this step SSA compute the eigenvalues and eigenvectors of matrix $\mathbf{XX}^T$ and represent it in the form of $\mathbf{XX}^T = P \wedge P^T$.

In this equation $\wedge$ = diag(λ_1,……, λ_L) is the diagonal matrix of eigenvalues of $\mathbf{XX}^T$ in a decreasing order ($\lambda_1 \geq . . . \geq \lambda_L \geq 0$) and P = (P_1, P_2,…, P_L) is the corresponding orthogonal matrix of eigenvector of $\mathbf{XX}^{T.}$ (Hassani 2009).

6.4.2 RECONSTRUCTION:

This section can be explained in two separate parts, grouping and diagonal averaging

6.4.2.1 GROUPING:

This section corresponds to splitting the elementary matrices $\mathbf{X}_i$ into several groups and summing the matrices within each group (Hassani 2009). If we consider $I = \{i_1,\ldots\ldots,i_l\}$as a group of indices $i_1,\ldots\ldots,i_l$.Then the matrix $\mathbf{X}_i$ corresponding to the group I is defined as $\mathbf{X}_I$ = $\mathbf{X}_{i1}+\ldots.+\mathbf{X}_{il}$.

6.4.2.2. DIAGONAL AVERAGING:

Diagonal averaging converts each matrix ***I*** into a time series, which is an additive component of the initial series Y (Hassani 2009). This stage in fact is a reconstruction of the one-dimensional series and compute:

$\widetilde{\mathbf{X}} = \| \tilde{x}_{i,j} \| = \sum_{k=1}^{l} \mathrm{P}_{ik} \mathrm{P}_{ik}^{T} \mathbf{X}$ Which is an approximation to **X**.

By averaging over the diagonals of the matrix $\widetilde{\mathbf{X}}$ a transition to the one-dimensional series can be achieved (Hassani 2009).

6.5 RESULTS:

By entering the data into Caterpillar SSA software, in the decomposition stage, no harmonic component or any kind of oscillation was identified in time series. For below knee time series, window length of 4 and for above knee window length of 5 were considered in embedding stage and the trend line was interpreting almost all the information of time series in both cases. Table 28 and Figure 10 illustrate the output of Caterpillar SSA for below knee time series. The first eigenvalue (trend line) interprets 99.94% of all the information of time series. Trend line is a slowly varying component of a time series which has not got any oscillatory components (Hassani 2007). By extracting the first eigentriple in SSA analysis, the trend line can be obtained (Hassani 2007).

Table 28: SSA output for below knee (L=4, R=1)

Year	**Actual values (s)**	**Forecast Based on initial series**
1976	14.40	14.40
1980	14.01	14.01
1984, New York/S.M.	13.62	13.62
1988, Seoul	12.37	12.37
1992, Barcelona	12.19	12.19
1996, Atlanta	11.78	11.78
2000, Sydney	11.40	11.4
2004, Athens	11.12	11.12
2008, Beijing	11.29	11.29
2012, London	11.00	11
2016, Rio		10.62

As forecasting an exact value for a parameter can be affected with many issues, it is good to provide a confidence interval for the forecasted value. In order to make confidence interval based on SSA technique, there are two methods: the empirical method and the bootstrap technique. The empirical confidence intervals are built for the entire series which is considered to have the same structure in the future (Hassani 2007). The bootstrap confidence intervals are constructed for the continuation of the signal which are the main components of the entire series (Golyandina et al. 2001). In this report only the bootstrap technique has been applied in order to find a 95% confidence interval for the forecast value.

Upper bootstrap limit = 10.72 (s)

Lover bootstrap limit = 10.30 (s)

Average bootstrap = 10.53 (s)

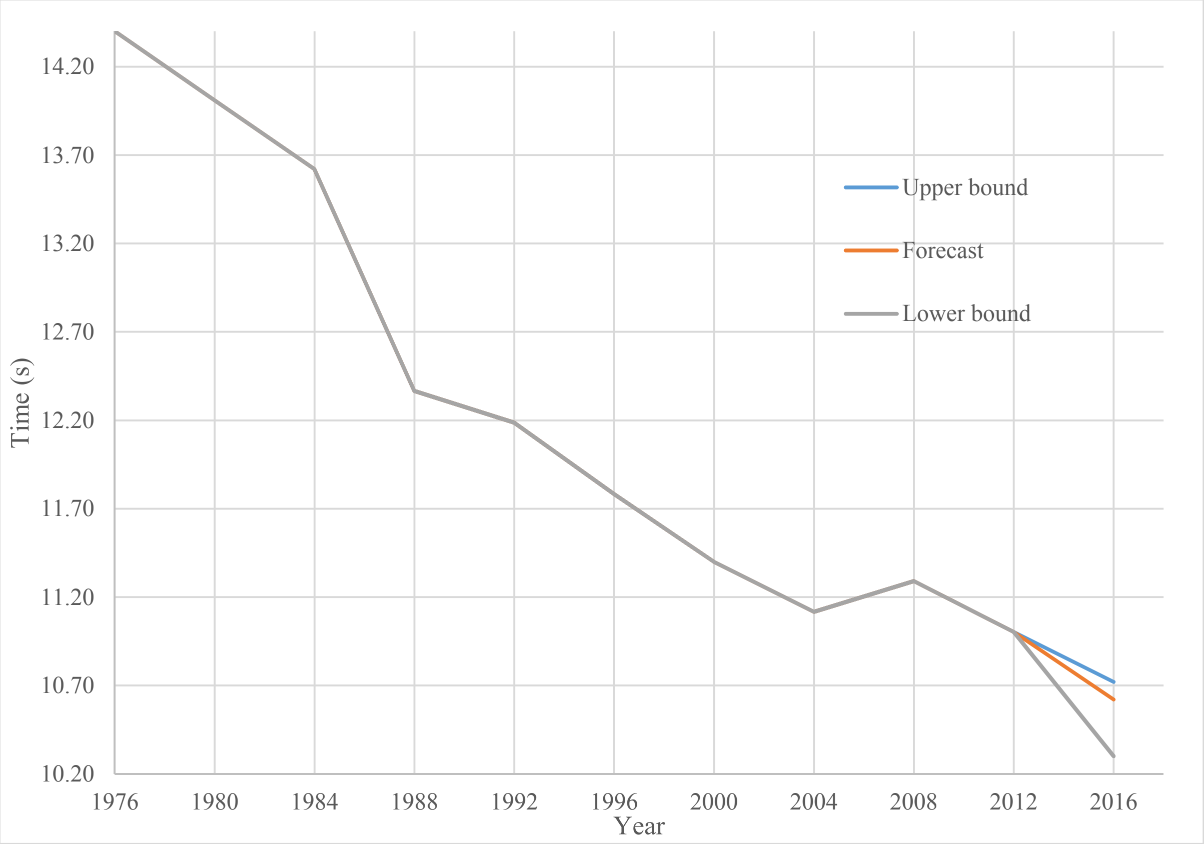

Figure 10: SSA output for 100m below knee (L=5, R=1)

Singular Spectrum Analysis suggests 10.62 seconds as a forecast for 2016 Paralympic Games for below knee amputees. Introduction of Energy Storage and Return foot (ESR) in 1988, caused a sharp decrease in the actual value and since then there has been a steady decrease for the average podium of Paralympic Games. Regarding to the discussed issues, 10.62 seconds, does not look a too ambitious record for below knee amputees in 2016.

In the below knee time series just the first eigenvalue (trend line) was considered as the only element which can interpret all of the information of time series and no harmonic component was considered. This issue could be justified through representation of squared roots of the singular values or the pared scatter plots of the eigenvectors.

Normally every harmonic component with a different frequency produces two eigentriples with close singular values (Hassani 2007). Figure 11 depicts the plot of the squared roots of the 5 singular values for the below knee series.

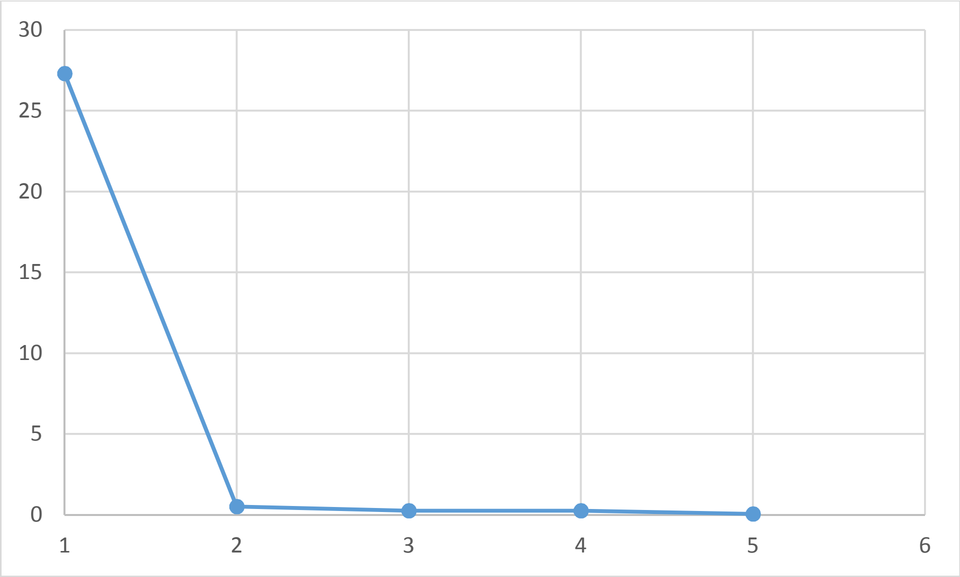

Figure 11: Squared roots for the 5 singular values.

A pure noise series, produces a slowly decreasing sequence of singular values (Haasani 2007). Considering the figure 1, it can be identified that there is not a pair of eigentriples with close singular values, and on the other hand the decreasing pattern of singular values in Figure 11, is quite clear. Considering the squared roots of singular values, it can be concluded that in this specific time series, no harmonic component exists and only the trend line can be considered in the reconstruction section.

The analysis of the pairwise scatterplots of the singular vectors allows to visually detect the eigentriples which correspond to the harmonic components of the series (Hassani 2007). If we consider a pure harmonic with a frequency ω, certain phase, amplitude and ideal situation where $P = 1/\ \omega$ is a devisor of the window length L and K, since P is an integer, it would be a period of the harmonic. In the ideal situation the left eigenvectors and principal components have the form of sine and cosine sequences with the same phase and same P (Hassani 2007). So, the identification of the components that are produced by a harmonic, can be reduced to the determination of these pairs. A pure harmonic component make the scatterplot with the points lying on a circle and creates the regular n-vertex polygon (Hassani 2007). Figure 12, depicts scatterplots of the paired eigenvectors in the below knee series.

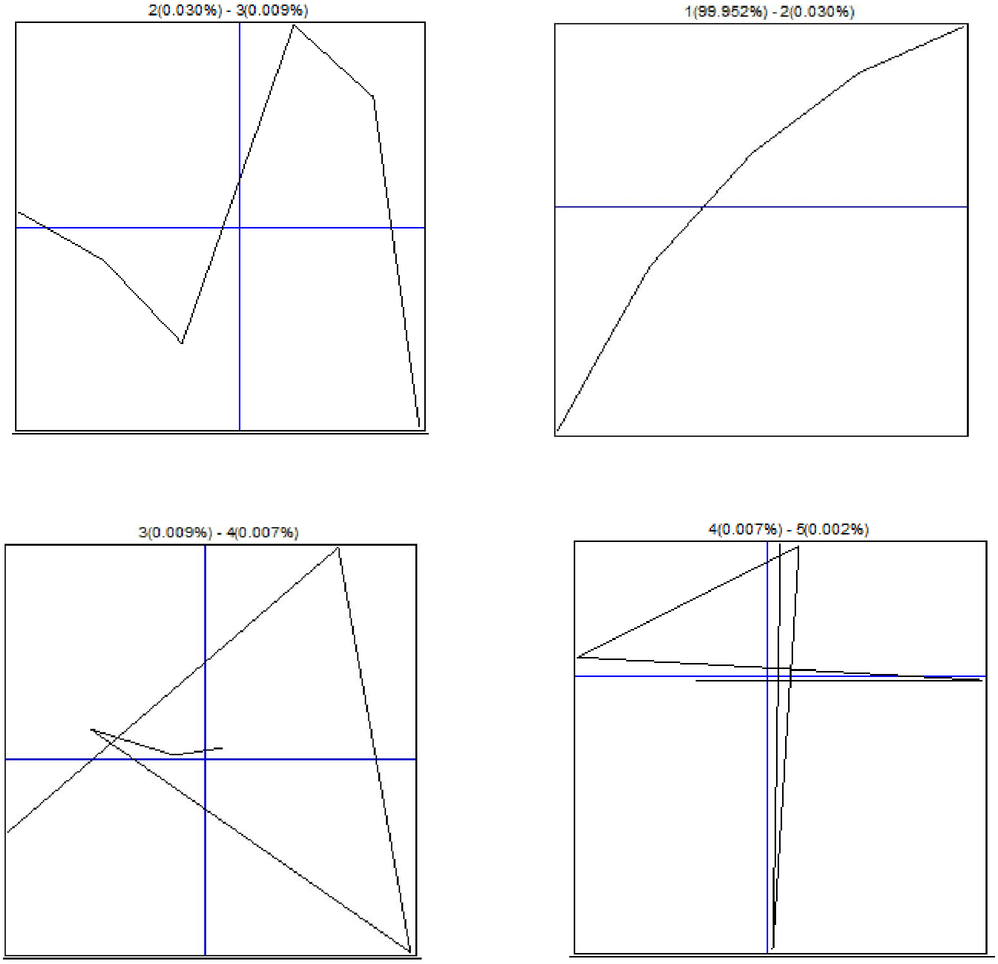

Figure 12: Scatterplots of the pared eigenvectores.

Considering the figure 12, it is obvious that the points are not laying on a circle and there is not a regular n-vertex polygon (not a clear shap), which can be concluded that in this case, there is not a harmonic component in the time series.

Singular Spectrum Analysis is based on the issue of "separability", which indicates that how well the different component of the series can be separated from each other (Hassani 2007). The decomposition in SSA can be successful only if the resulting additive components of the time series are separable from each other (Hassani 2007). The dependence between two series can be measured by weighed correlation (or *ω-correlation*). *ω-correlation* matrix, is a perfect method to distinguish noise from signal. If the value of *ω-correlation* is small, then the corresponding series are almost *ω*-orthogonal, and if it is large, then the two series are badly separable (Hassani 2007). Figure 13, indicates the *ω- correlation* for 5 reconstructed components in a grey scale from white to black (corresponding to the absolute values of correlation from 0 to 1).

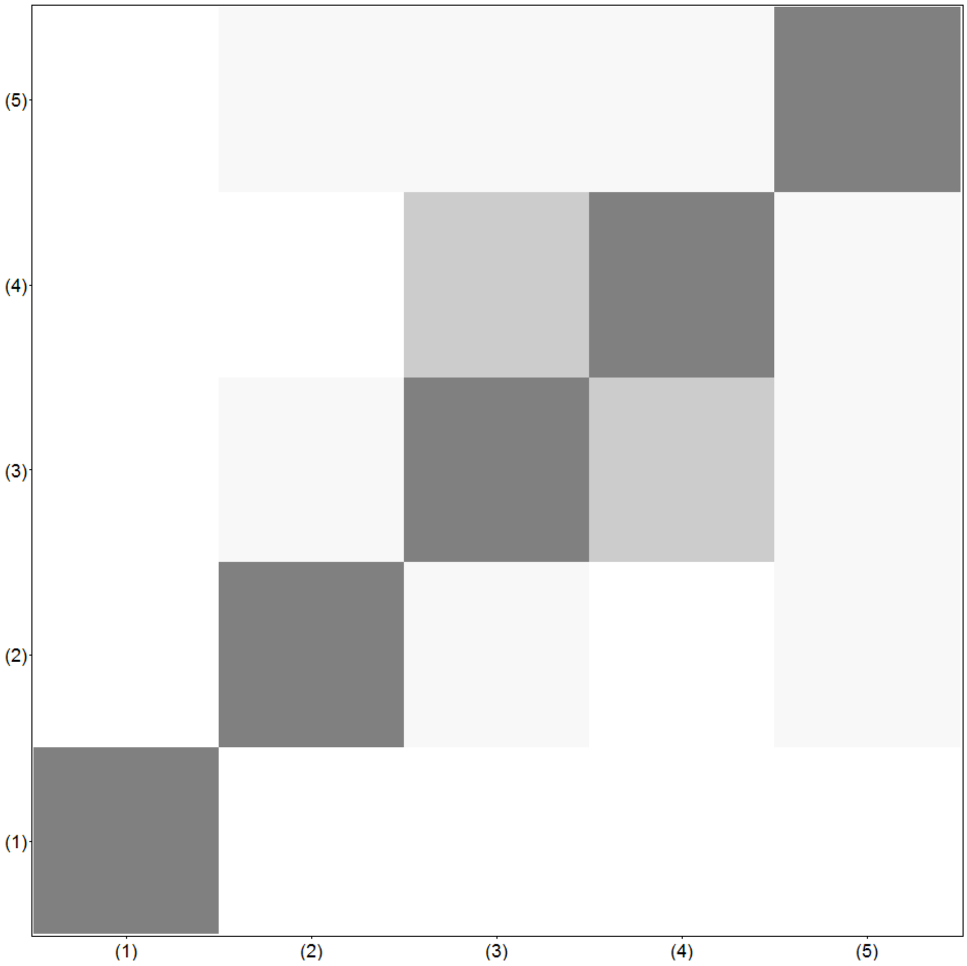

Figure 13: matrix of *ω-correlation* for the 5 reconstructed components.

The *ω-correlation* matrix represents a clear separability between the first component and the other 4 components which can be considered as the noise. After the reconstruction stage, the residual diagram can be extracted from the rest of time series. Figure 14, represents the residual diagram, after considering the first eigenvalue in the grouping stage.

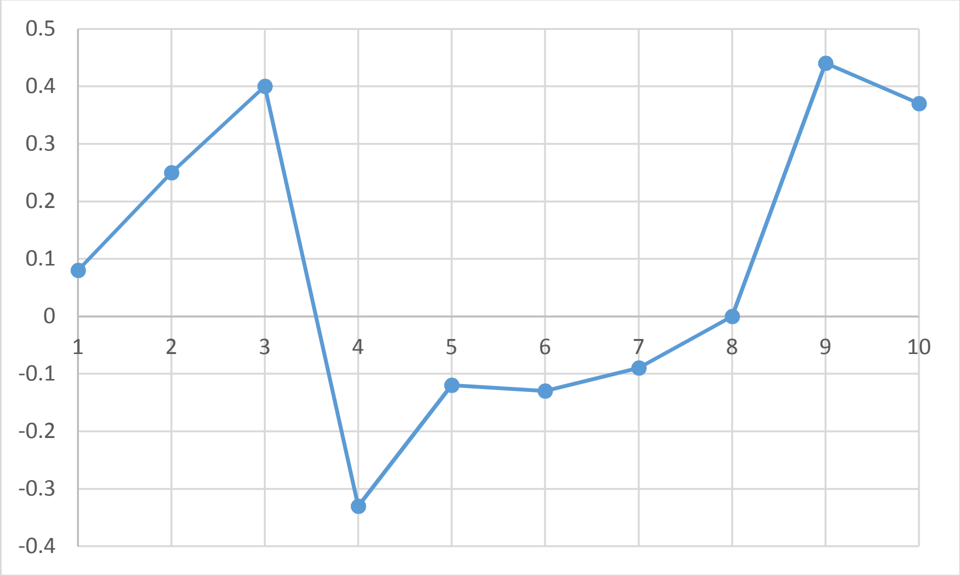

Figure 14: Residual diagram for the below knee time series.

The residual values are fluctuating between -0.34 and +0.44. Considering the actual values in the time series, it is quite clear that any other component, except the trend line, has got a really little contribution to the reconstruction of series and can be considered as the noise.

Table 29 and Figure 15 represent the results of Caterpillar SSA for above knee time series. The first eigenvalue (trend line) interprets 99.85% of all the information of time series.

Table 29: SSA output for above knee (L=4, R=1).

Year	**Actual values**	**Forecast Based on initial series**
1984, New York/S.M.	17.44	17.44
1988, Seoul	16.23	16.23
1992, Barcelona	13.87	13.87
1996, Atlanta	14.07	14.07
2000, Sydney	12.96	12.96
2004, Athens	12.76	12.76
2008, Beijing	12.79	12.79
2012, London	12.45	12.45
2016, Rio		11.79

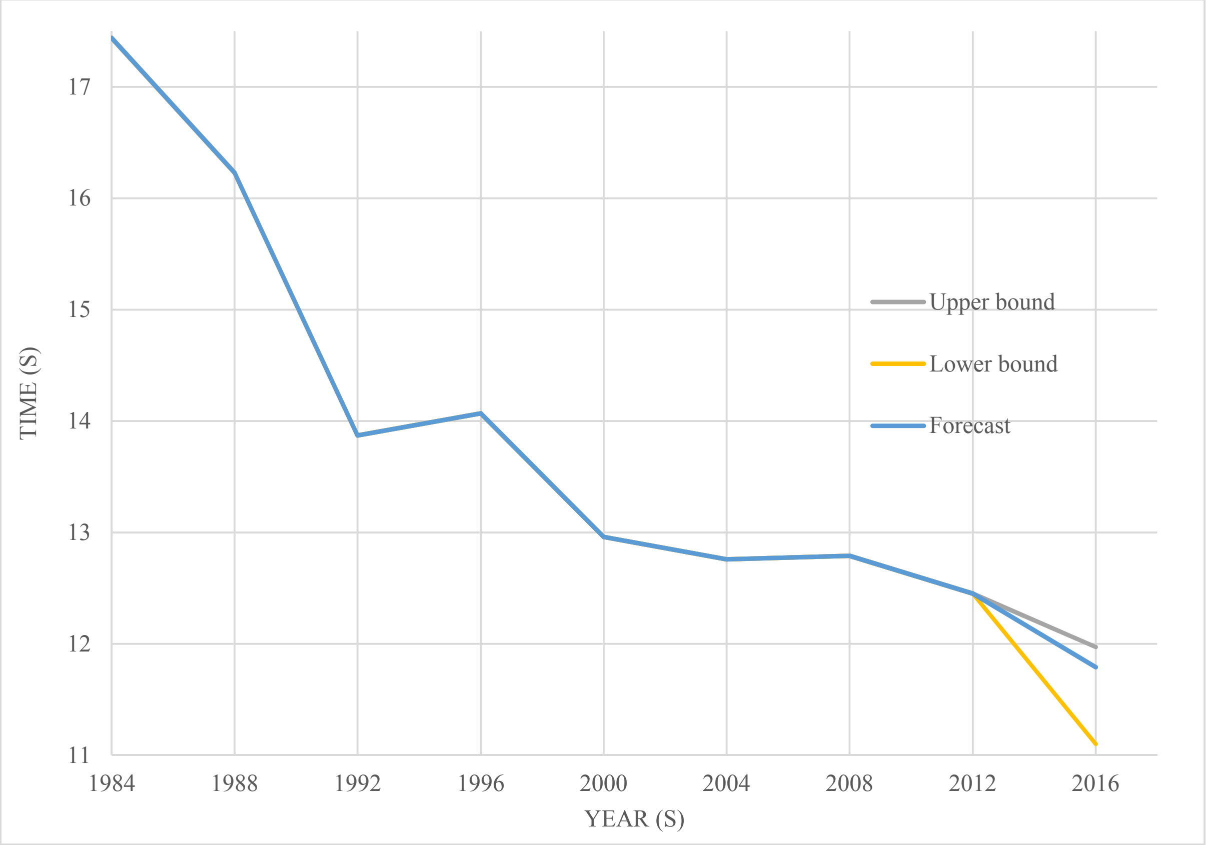

Figure 15: SSA output for 100m above knee (L=4, R=1)

Figure 15 indicates that by the introduction of ESR foot in elite sports, the average podium of above knee amputees, faced a sharp decrease, and since 1992, there has been a steady decrease in the results for the athletes. Regarding these issue, 11.79 second does not look a very ambitious record for 2016 for this category of amputees in Paralympic Games.

The results of bootstrap technique can be summarized as:

Upper bootstrap limit = 11.97 (s)

Lover bootstrap limit = 11.10 (s)

Average bootstrap = 11.50 (s)

A comparison between the forecasted values for Olympics and Paralympics, can illustrate that how the results of competition in these two special sports event can get close to each other in future. In order to do so, based on the available information in Table 19 a forecast for

2016 Olympics has been provided. Table 30 and Figure 16 represent the results of Caterpillar SSA for Olympic time series.

Table 30: SSA output for Olympic (L=4, R=1).

Year	**Actual values**	**Forecast Based on initial series**
1984, New York/S.M.	10.13	10.13
1988, Seoul	9.96	9.96
1992, Barcelona	10.01	10.01
1996, Atlanta	9.88	9.88
2000, Sydney	9.97	9.97
2004, Athens	9.86	9.86
2008, Beijing	9.83	9.83
2012, London	9.72	9.72
2016, Rio		9.68

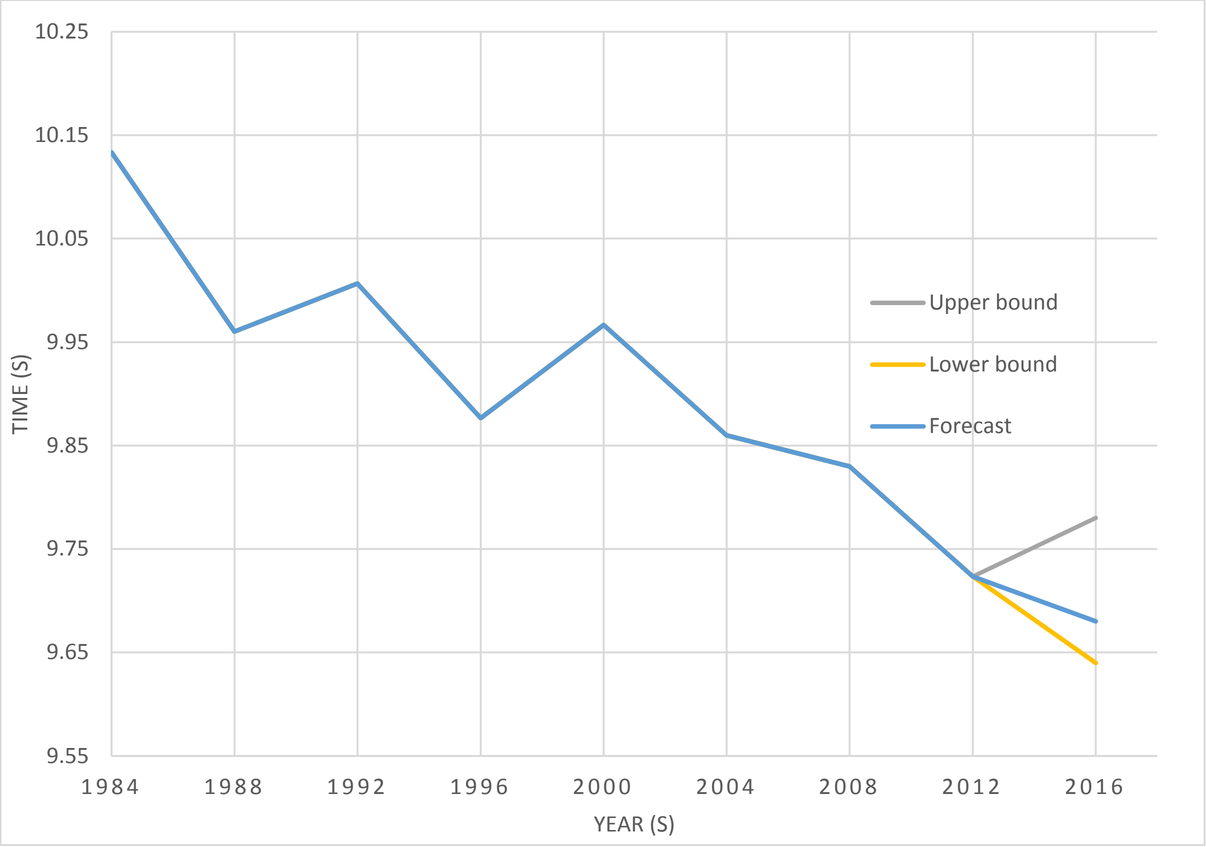

Figure 16: SSA output for 100m Olympic (L=4, R=1)

The results of bootstrap technique can be summarized as:

Forecast (SSA) = 9.68 (s)
Upper bootstrap limit = 9.78 (s)
Lover bootstrap limit = 9.64 (s)
Average bootstrap = 9.70 (s)

The forecasted value for 2016 Olympic, has been based on considering only the first eigenvalue (trend line) in the reconstruction stage of SSA. In this time series no harmonic component or any kind of oscillation was identified. A comparison between the forecasted values for Olympics and below knee Paralympics, represents a difference of only 0.94 (s) in the performance. This gap for 2012 Paralympic and Olympic Game was 1.28 (s) (a comparison between the podium of 2012 results for Olympics and below knee Paralympics). These results indicates that in the future even the existing gap between Olympic and Paralympic Games will get smaller and smaller and this would be mainly due to technological improvements which would assist amputees in elite sports.

Although the analysis in this section of the thesis has been based on the trend line and it can be extracted with some easier methods (Excel, etc.), but it worth to mention that, SSA provides us with more flexibility and the timeseries can be built based on all the effective eigenvalues. Moreover we remove noise and we know that small changes in the trend line will make a huge difference in projection.

CONCLUSIONS:

This thesis provided an overview on the performance of the amputees in Paralympic Games in running activity. At the beginning of this thesis, the history of the Paralympic Games and the prosthesis, provides a good insight to the topic for the reader. After this literature of review, a number of important issues in running activity in Paralympic Games have been introduced and addressed based on some statistical analyses (with the support from mechanical knowledge).

The results of this thesis indicated that in running events above 100m bilateral amputees take advantage of symmetry in their running activity and run faster comparing to unilateral amputees. This idea has been proved based on some statistical analyses and also mechanical justifications have been added to support the idea. However considering the available historical data at the Paralympics database, does not prove any advantage for bilateral amputees over able-bodied athletes. In fact human ankle can perform better than any other joint ever built by humans in running exercise (Nolan 2008). The major differences between amputees and non-amputees in running activity can be attributed to the absence of ankle plantar flexor muscles, which provide needed body support, forward population and swing initiation during non-amputee running (Neptune et al. 2001).

In order to ensure that the competition in Paralympic Games is fair, there is a system in place for all of the Paralympic sports which ensures that the winning is based on power, fitness, skill, tactical ability and mental focus. This process is called classification and its purpose is minimizing the impact of impairment on activity (sport discipline). Based on this definition, the impact of disability on sports must be considered instead of just considering the type of impairment. Through this system, it is determined which athletes are eligible to compete in a sport and how athletes are grouped together for competition. Classification is sport specific as impairment affects the ability to perform in different sport to a different extent (Dyer 2013). The scope for considering the fairness of Paralympic Games is huge as it requires comprehensive literature of review in terms of legislation, the type of prosthesis used by the athletes and affordability of buying these prostheses by all of the athlete who participate in this sport event (sport with equal opportunities). However the scope of this research has been limited to evaluating the existing framework in running exercise which is defined by IPC.

This research considered mainly the impact of type of disability (unilateral or bilateral) on fairness of sport. However, the type of prosthesis (c or j shaped blade) can be an effective element in the outcome of the competition. In order to provide a fair competition, it can be proposed that, all the athletes who participate in Paralympics, should be provided with the same type pf prosthesis, which can be sponsored by the companies who are producing sports clothes and facilities (like Nike, Adidas etc.). These companies through advertising (like having their logo on prosthesis, media or posters on the venue), can invest in a project which is financially justified.

Regarding to the classification system in Paralympic Games, the results of this thesis indicate that some of the existing classifications have a better performance comparing to other classifications (advantage of T44 over T42) and proves that the length of the amputation can significantly affect the results of the competition. It also proves that some of the existing classifications in Paralympic Games are not fair and they need to be adjusted. The results in this report proves that T43 classification has an advantage comparing to T44. At the moment T44 and T43 has been mixed up and it has been considered as T44 (due to low level of participation in T43). Based on the statistical analyses represented in this report, the governing bodies should revise the existing classification and there should be two separate competitions for each of these groups.

The results in this report illustrate how technology inclusion can enhance amputee's performance in running activity. The early models of prostheses in professional sport produced the minimum amount of energy storage and return due to the limited deflection and high stiffness (Nolan 2008). In order to address this problem, ESR foot was invented. The invention of ESR foot introduced the concept of energy storage and return in prosthesis design and resulted into a significant change in the performance of amputees in professional sports. The analyses in this thesis proves that the introduction of ESR foot significantly changed the results of the competition in Paralympic Games. Considering the available historical data at the Paralympics database, it can be identified that after the invention of ESR the completion time of the game by the athletes in Paralympic Games, had a sharp decline. By the developments of the carbon fiber prosthesis the amputees are regaining not only the function of missing anatomical part of the body, but they are able to have a better performance in professional sport from what they used to have, and today the margin between their performance and able-bodies athletes has become so small. However inclusion of technology should not be in contradiction with the nature of sport and should not give an unfair advantage to only a limited group of athletes. Legislation of the sport regarding to the use of technology, must be consistently upgraded in order to address all these issues.

Several analyses and diagrams in this thesis represented the differences between Olympic and Paralympic Games in running exercise. The results of Paralympic Games shows higher level of variation (based on two numeric parameter of standard deviation and PII) and the reasons of this high variation has been clarified within the thesis. Historical data indicate the Olympians has had a better performance comparing to Paralympians and the track 400m, T44 London 2012 was introduced as a point where the gap between Paralympics and Olympics can be minimized. The results of analyses indicate that even in this point Olympians run faster than Paralympians.

Also some novel approaches like Singular Spectrum Analysis (SSA) has been used to provide a forecast for 2016 Paralympic Games. This will provide an insight for the governing bodies in Paralympic Games that where the sport is going to. Also the forecasted values represent the fact that in the future the results in Paralympic Games will get closer to the results of Olympics. The publication of such works can change people's perception of disability in society and it will send the message of what they are able to do, rather than what they cannot do. The results of SSA indicated that the first eigenvalue (trend line) is the only component which can be considered in the reconstruction stage and no harmonic component or oscillation was identified in all of the time series in this thesis. This issue has been proved for below knee time series based on squared roots for singular values, scatterplots of paired eigenvectors, and ω correlation matrix. Also bootstrap technique has been added to the analyses in this report, in order to provide a confidence interval for forecasted values. As forecasting of a parameter could be affected with many issues, providing a range (rather than an exact value) is highly important.

FUTURE WORK:

In most of the cases analyses in this thesis has been limited to the database provided by IPC in the official website of Paralympic Games. In some cases the dataset was not large enough and also in some other cases, the data generated by one person (in different track events) has been used to increase the sample size which will causes repeated measure. In order to address these problems some simulated dataset can be used instead of historical Paralympic results. The process of data collection can be done within a collaborated work with mechanical engineers in a laboratory to provide a database which has not got the existing problems. Then some novel approaches like Singular Spectrum Analysis can be applied to extract the trend line (a noise free data). Having a comparison between the trend lines by the help of some statistical techniques, can support the result gained in this thesis.

Also in some parts of this thesis, the mechanical justifications can be widely enhanced. Doing a more comprehensive literature review on the history of prosthesis and elite sport for amputees, can provide a better background for the readers. Gaining a good knowledge in gate analysis, can surely support the results of this thesis.

It is needed to acknowledge that the forecasting in this thesis is in-sample forecast. In this method, the model is estimated using all the available data up to present time, and then compares the model's fitted values to the actual realizations. There are some out of sample analysis methods as well which re-estimate the model in each time interval and make a new forecast for future. The results of the analyses based on out-of-sample forecast can be compared to the results of this thesis, and with evaluating the error, the ability of different models in forecasting can be compared.

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APPENDIX 1:

Table 1: 100m/First Round/Heat 1/ T42/London 2012.

Rank	Athlete(s)	Country	Results (s)	Specification
1	Popow, Heinrich	GER	12.43	1 leg
2	Reardon, Scott	AUS	12.45	1 leg
3	Whitehead, Richard	GBR	12.97	2 leg
4	Vance, Shaquille	USA	13.17	1 leg
5	Sveinsson, Helgi	ISL	15.64	1leg
6	Pilgrim, Jamol Allan	ANT	15.76	1leg

Table 2: 100m/First Round/Heat 2/ T42/London 2012.

Rank	Athlete(s)	Country	Results (s)	Specification
1	Czyz, Wojtek	GER	12.53	1leg
2	Connor, Earle	CAN	12.56	1 leg
3	Kayitare, Clavel	FRA	12.59	0 leg
4	Yamamoto, Atsushi	JPN	12.87	1 leg
5	Jorgensen, Daniel	DEN	13.21	1 leg
6	Garcia-Tolson, Rudy	USA	13.77	2 leg

Table 3: 100m/Final round/ T42/London 2012.

Rank	Athlete(s)	Country	Results (s)	Specification
1	Popow, Heinrich	GER	12.4	1 leg
2	Reardon, Scott	AUS	12.43	1 leg
3	Czyz, Wojtek	GER	12.52	1 leg
4	Connor, Earle	CAN	12.65	1 leg
5	Kayitare, Clavel	FRA	12.73	0 leg
6	Yamamoto, Atsushi	JPN	12.92	1 leg
7	Whitehead, Richard	GBR	12.99	2 leg
8	Vance, Shaquille	USA	13.03	1 leg

Table 4: 100m/First Round/Heat 1/ T44/London 2012.

Rank	Athlete(s)	Country	Results (s)	Specification
1	Peacock, Jonnie	GBR	11.08	1 leg
2	Singleton, Jerome	USA	11.46	1 leg
3	Oliveira, Alan Fonteles Cardoso	BRA	11.56	2 leg
4	Fernandes, Marcio Miguel Da Costa	CPV	12.16	1 leg
5	Behre, David	GER	12.27	2 leg
6	Scendoni, Riccardo	ITA	12.45	1 leg
7	Jia, Tianlei	CHN	12.49	1 leg

Table 5: 100m/First Round/Heat 2/ T44/London 2012.

Rank	Athlete(s)	Country	Results (s)	Specification
1	Pistorius, Oscar	RSA	11.18	2 leg
2	Leeper, Blake	USA	11.34	2 leg
3	Liu, Zhiming	CHN	11.84	0 leg
4	Rehm, Markus	GER	11.92	1 leg
5	Alaize, Jean-Baptiste	FRA	12.11	1 leg
6	Prokopyev, Ivan	RUS	12.21	2 leg
7	Mayer, Robert	AUT	12.61	1 leg

Table 6: 100m/First Round/Heat 3/ T44/London 2012.

Rank	Athlete(s)	Country	Results (s)	Specification
1	Fourie, Arnu	RSA	11.29	1 leg
2	Browne, Richard	USA	11.33	1 leg
3	McQueen, Alister	CAN	12.02	1 leg
4	Bausch, Christoph	SUI	12.09	1 leg
5	Oliveira, Andre	BRA	12.35	2 leg
6	Haruta, Jun	JPN	12.69	1 leg

Table 7: 100m/Final round/ T44/London 2012.

Rank	Athlete(s)	Country	Results (s)	Specification
1	Peacock, Jonnie	GBR	10.9	1 leg
2	Browne, Richard	USA	11.03	1 leg
3	Fourie, Arnu	RSA	11.08	1 leg
4	Pistorius, Oscar	RSA	11.17	2 leg
5	Leeper, Blake	USA	11.21	2 leg
6	Singleton, Jerome	USA	11.25	1 leg
7	Oliveira, Alan Fonteles Cardoso	BRA	11.33	2 leg
8	Liu, Zhiming	CHN	11.97	0 leg

Table 8: Table 7: 200m/ T42/London 2012.

Rank	Athlete(s)	Country	Results (s)	Specification
1	Whitehead, Richard	GBR	24.38	2 leg
2	Vance, Shaquille	USA	25.55	1 leg
3	Popow, Heinrich	GER	25.9	1 leg
4	Reardon, Scott	AUS	26.03	1 leg
5	Czyz, Wojtek	GER	26.07	1 leg
6	Kayitare, Clavel	FRA	26.22	0 leg
7	Jorgensen, Daniel	DEN	26.46	1 leg
8	Yamamoto, Atsushi	JPN	26.76	1 leg
9	Garcia-Tolson, Rudy	USA	26.97	2 leg

Table 9: 200m/First Round/Heat 1/ T44/London 2012.

Rank	Athlete(s)	Country	Results	Specification
1	Oliveira, Alan Fonteles Cardoso	BRA	21.88	2 leg
2	Singleton, Jerome	USA	23.23	1 leg
3	McQueen, Alister	CAN	24.25	1 leg
4	Prokopyev, Ivan	RUS	24.26	2 leg
5	Alaize, Jean-Baptiste	FRA	24.42	2 leg
6	Swift, Jack	AUS	24.88	1 leg

Table 10: 200m/First Round/Heat 2/ T44/London 2012.

Rank	Athlete(s)	Country	Results	Specification
1	Leeper, Blake	USA	22.23	2 leg
2	Fourie, Arnu	RSA	22.57	1 leg
3	Behre, David	GER	23.65	1 leg
4	Bausch, Christoph	SUR	24.22	1 leg
5	Mayer, Robert	AUT	24.67	1 leg
6	Jia, Tianlei	CHN	25.62	1 leg

Table 11: 200m/First Round/Heat 3/ T44/London 2012.

Rank	Athlete(s)	Country	Results (s)	Specification
1	Pistorius, Oscar	RSA	21.3	2 leg
2	Bizzell, Jim Bob	USA	23.64	1 leg
3	Sato, Keita	JPN	24.34	1 leg
4	Scendoni, Riccardo	ITA	24.51	1 leg
5	Fernandes, Marcio Miguel Da Costa	CPV	24.84	1 leg
6	Pituwala Kankanange, Dumeera Maduranga Alwis	SRI	26.23	0 leg

Table 12: 200m/Final Round/T44/London 2012.

Rank	Athlete(s)	Country	Results (s)	Specification
1	Oliveira, Alan Fonteles Cardoso	BRA	21.45	2 leg
2	Pistorius, Oscar	RSA	21.52	2 leg
3	Leeper, Blake	USA	22.46	2 leg
4	Fourie, Arnu	RSA	22.49	1 leg
5	Singleton, Jerome	USA	23.58	1 leg
6	Bausch, Christoph	SUI	23.7	1 leg
7	Behre, David	GER	23.71	1 leg
8	Bizzell, Jim Bob	USA	28.19	1 leg

Table 13: 400m/First Round/Heat 1/ T44/London 2012.

Rank	Athlete(s)	Country	Results	Specification
1	Leeper, Blake	USA	50.63	2 leg
2	Oliveira, Alan Fonteles Cardoso	BRA	53.02	2 leg
3	Liu, Zhiming	CHN	54.82	0 leg
4	Scendoni, Riccardo	ITA	55.88	1 leg
5	Swift, Jack	AUS	55.94	1 leg
6	Benitez Sandoval, Josue	MEX	59.79	1 leg

Table 14: 400m/First Round/Heat 2/ T44/London 2012.

Rank	Athlete(s)	Country	Results	Specification
1	Pistorius, Oscar	RSA	48.31	2 leg
2	Behre, David	GER	51.37	2 leg
3	Prince, David	USA	52.29	1 leg
4	Wallace, Jarryd	USA	53.51	1 leg
5	Prokopyev, Ivan Sato, Keita	RUS	53.86	2 leg

Table 15: 400m/Final Round/ T44/London 2012.

Rank	Athlete(s)	Country	Results	Specification
1	Pistorius, Oscar	46.68	RSA	2 leg
2	Leeper, Blake	50.14	USA	2 leg
3	Prince, David	50.61	USA	1 leg
4	Oliveira, Alan Fonteles Cardoso	51.59	BRA	2 leg
5	Behre, David	51.65	GER	2 leg
6	Wallace, Jarryd	53.9	USA	1 leg
7	Prokopyev, Ivan	54.74	RUS	2 leg
8	Liu, Zhiming	55.91	CHN	0 leg

APPENDIX 2:

Table 1: 100m Descriptive data for 2008 Beijing.

Category	N	Mean	Median	s.d	Min	Max	S-W
T42/Final	6(0,6,0)	13.11	13.08	0.53	12.32	13.68	0.717
T44/Heat 1	6(0.5.1)	11.9	11.96	0.25	11.49	12.12	0.299
T44/Heat 2	6(1.4.1)	12.15	12.04	0.83	11.16	13.45	0.801
T44/Final	8(1,7,0)	11.64	11.56	0.41	11.17	12.25	0.676

Table 2: 200m Descriptive data for 2008 Beijing.

Category	N	Mean	Median	s.d	Min	Max	S-W
T44/Heat 1	5(1,4,0)	24.81	24.17	2.01	23.22	28.32	0.025
T44/Heat 2	5(1,3,1)	24.09	24.22	0.93	22.71	24.95	0.495
T44/Final	8(2,5,1)	23.36	23.47	0.93	21.67	24.61	0.939

Table 3: 400m Descriptive data for 2008 Beijing.

Category	N	Mean	Median	s.d	Min	Max	S-W
T44/Final	6(1.4.1)	52.43	52.42	3.099	47.49	55.76	0.644

Table 4: 100m Descriptive data for 2004 Athens.

Category	N	Mean	Median	s.d	Min	Max	S-W
T42/Final	6(0,5,1)	13.41	13.04	1.085	12.51	15.5	0.052
T44/Heat 1	5(0,5,0)	12.41	12.57	0.73	11.23	12.95	0.115
T44/Heat 2	6(1,5,0)	11.88	11.93	0.515	11.2	12.52	0.74
T44/Final	8(1,7,0)	11.7	11.695	0.561	11.08	12.58	0.36

Table 5: 200m Descriptive data for 2004 Athens.

Category	N	Mean	Median	s.d	Min	Max	S-W
T42/Final	6(0,5,1)	27.12	27.1	0.677	26.18	28.1	0.959
T44/Heat 1	6(1,5,0)	24.71	24.51	1.079	23.42	26.55	0.759
T44/Heat 2	6(0,6,0)	24.81	24.48	1.053	23.5	26.18	0.427
T44/Final	8(1,7,0)	23.15	23.2	0.659	21.97	23.87	0.427

Table 6: 400m Descriptive data for 2004 Athens.

Category	N	Mean	Median	s.d	Min	Max	S-W
T44/ Heat 1	5(0,5,0)	55.38	55.67	1.236	53.58	56.7	0.794
T44/Heat 2	4(0,4,0)	55.36	54.31	2.229	54.12	58.7	0.006
T44/Final	7(0,7,0)	53.76	53.98	1.295	51.24	55.02	0.268