

**KINEMATIC DIFFERENCES BETWEEN THREE
WHEELCHAIR RACERS (T54) IN SPRINT START**

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Master's Thesis in Biomechanics

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ABSTRACT

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This study examined kinematic differences between wheelchair racers (T54) in sprint start. Three male elite disabled athletes performed maximum trials four times, 80 % of maximum and 60 % of maximum two times. Two-dimensional motion analysis was used to study the fastest trial (100 % of Max) and the closest trial to the 80 % of Max and 60 % of Max. The kinematic variables measured were: a) timing parameters; push time, recovery time and cycle time, b) linear velocities; the velocity of the wheelchair, the wrist and the elbow velocities in different cycles in the different trials c) angular parameters; trunk and shoulder angle and trunk angular velocity, contact angle and range of push angle and d) the point of contact and release.

In this case study it was found that the racer with more velocity had smaller time on the propulsive phase and increased forward body movement in relation to the axle of wheel at start. In addition, the racer with more velocity had larger velocity of the wrist in the end of the recovery phase and had larger velocity of the elbow in the beginning of the propulsive phase.

The sample sizes within a disability classification are quite small and limit generalisations which could be made about the findings to the population under consideration. Moreover, the differences in the testing modes and protocols make comparisons among different studies difficult. However, results demonstrate that the kinematic variables recorded prior to contact and on hand contact with the pushrim are more important in developing more efficient racing wheelchair propulsion. The results of this study indicate a need to educate coaches of wheelchair track athletes concerning the most efficient start technique of racing wheelchair propulsion.

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Tämän tutkimuksen tarkoituksena oli tutkia kinemaattisten muuttujien eroja ratakelaajilla (T54) startissa. Kolme vammaishuippu-urheilijaa suoritti neljä kertaa maksimaalisen startin, joiden lisäksi kaksi kertaa 80 % ja 60 % startin. Kolmesta suorituksesta (100 % Max, 80 % Max ja 60 % Max) tehtiin kaksi-dimensionaalinen liikeanalyysi, jolla analysoitiin: a) työntö- ja palautusaika sekä koko sykliin käytetty aika, b) pyörätuolin, ranteen ja kyynärpään nopeus syklin eri vaiheissa, c) vartalon ja olkapään kulma, vartalon kulmanopeus sekä kontakti- ja työntökulma ja d) kontakti- ja irrottamiskohta.

Tutkimuksessa havaittiin, että nopeuden kasvaessa työntöaika pieneni ja vartalon kulmamuuutokset pienenivät. Lisäksi nopean kelaajan ranteen lineaarinen nopeus oli suurempi palautusvaiheen lopussa ja kyynärpään lineaarinen nopeus suurempi työntövaiheen alussa kuin hitaammalla kelaajalla.

Tutkimuksen tuloksia ei voida yleistää pienen koehenkilömäärän takia. Erilaiset määritelmät, tutkimusmenetelmät ja –asetelmat myös hankaloittivat tulosten vertailua muihin tutkimuksiin. Tämän tutkimuksen perusteella voidaan kuitenkin osoittaa, että ennen työntövaihetta ja sen aikana mitatut kinemaattiset muuttujat ovat tärkeitä tehokkaalle kelaamiselle. Vammaisyleisurheilvalmentajien tulisi täten ymmärtää ja hyödyntää niitä tekijöitä, jotka saavat aikaan mahdollisimman optimaalisen lähtötekniikan.

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1 INTRODUCTION

Disabled athletes have got a growing publicity in media in Finland after the medals won from Athens Paralympic Games 2004, especially from wheelchair racing. Since then there has been a growing interest towards disabled athletes in general. But there are still very few studies done in this field.

Wheelchair racing is one of the events in athletics. The events of wheelchair racing can be compared to running events. Since the wheelchair-user combination is non-stationary, wheelchair propulsion is complicated to measure. There are a lot of movements in wheelchair propulsion appearing almost at the same time: upper limb flexion/extension and abduction/adduction; joints of shoulder, elbow and wrist move at the same time; muscles of every moving segment generate different parallels and in amounts of forces that change all the time. (Wang et al. 1995.) There are some articles dealing with the kinematic variables in wheelchair racing propulsion (Chow et al. 2001; Higgs 1986; O'Connor et al. 1998; Ridgway et al. 1988; Wang et al. 1995), but there are almost no published articles examining the sprint start of wheelchair racing. Very few studies have measured racing wheelchair propulsion in natural environment and different researchers have used different definitions for the same variables (O'Connor et al. 1998; Moss et al. 2005).

The start is obviously crucial and very important to master if a racer wants to maximize ones performance over the race distance. Wheelchair athletes are continually looking for new and enhanced ways to train and/or analyze their propulsion technique. Racing times are getting better and better so that small increments of change can lead to world records. This is one the reasons why this study is made and why it is so important for athletes and their coaches.

The purpose of the present study was to examine kinematic differences between wheelchair racers (T54) in sprint start.

2 SPINAL CORD, SPINAL CORD INJURY (SCI), NEUROMUSCULAR DISEASES AND CLASSIFICATION

There are about one hundred new cases of severe SCI in Finland every year. There is about 3000-4000 in total of SCIs in Finland. Two thirds of them are wheelchair users. (Dahlberg & Alaranta 1996.) Accidents are 70-85 % the cause of SCIs and the rest are caused by neuromuscular diseases. The main general reasons for accidents are traffic (41,8 %), falling (37,4 %) and work. (Alaranta & Ahoniemi 1998.) Accidents caused by stumbling and slipping have doubled as well (Alaranta et al. 2000). Diving accidents are rarer, although there are still about 2-6 diving accidents every summer (Alaranta & Ahoniemi 1998). Relatively, cycling accidents are growing at this time with the accidents caused by snowmobiles. Cycling accidents cover 4,1 % and sport covers 3,9 % of all accidents. (Alaranta et al. 2000.) Motocross and ice hockey are extremely risky sporting events. Still, sport accidents are very rare in Finland comparing to other countries. It seems to be tied to the geographical location. (Valtonen & Alaranta 2001.) It is apparent that the amount of women and the middle-aged are increasing the case numbers (Alaranta et al. 2000).

Tetraplegia is result of the damage of the cervical segments of the spinal cord (Alaranta et al. 1998). Upper and lower limbs and pelvic organs have more or less functional impairment. At that time sense of touch can also be lost. The levels of lesion of brachial plexus or peripheral nerves outside the neural canal do not include tetraplegia. (Maynard et al. 1997.) Paraplegia is a lesion of the thoracic, lumbar or sacral segments of the spinal cord and it is almost as common as tetraplegia (Alaranta et al. 1998).

2.1 Spinal nerves and the structure of spinal cord

The spinal nerves are transmitted through the intervertebral foramina on either side of the spinal column. There are thirty-one pairs of spinal nerves, which are arranged into the region of the spine through which they pass: Cervical (8 pairs, C1-C8), Dorsal/Thoracic (12 pairs, T1-T12), Lumbar (5 pairs, L1-L5), Sacral (5 pair, S1-S5) and Coccygeal (1 pair, Co1) (Fig. 1). Each spinal nerve arises by two roots; an anterior motor root and a posterior sensory root (Gray 1974) (Fig. 1).

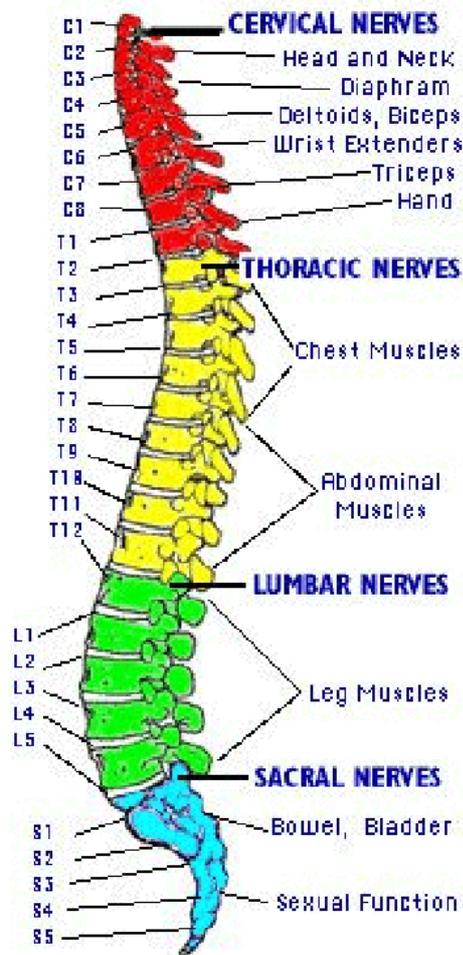


FIGURE 1. Spinal Nerves. Missing Coccygeal nerve (The Spinal Cord Injury Resource Center 2008).

The spinal cord (medulla spinalis) is contained in the vertebral canal. It is the connection center for the reflexes as well as the afferent (sensory) and efferent (motor) pathways for the most of the body, with the exception of the cranial nerves, to the head and neck. It does not nearly fill the canal but there is also areolar tissue, a plexus of veins, nerves and liquid cerebro-spinal. Spinal cord goes all the way to the level of L1 (Gray 1974) (Fig. 2).

The Spinal Cord

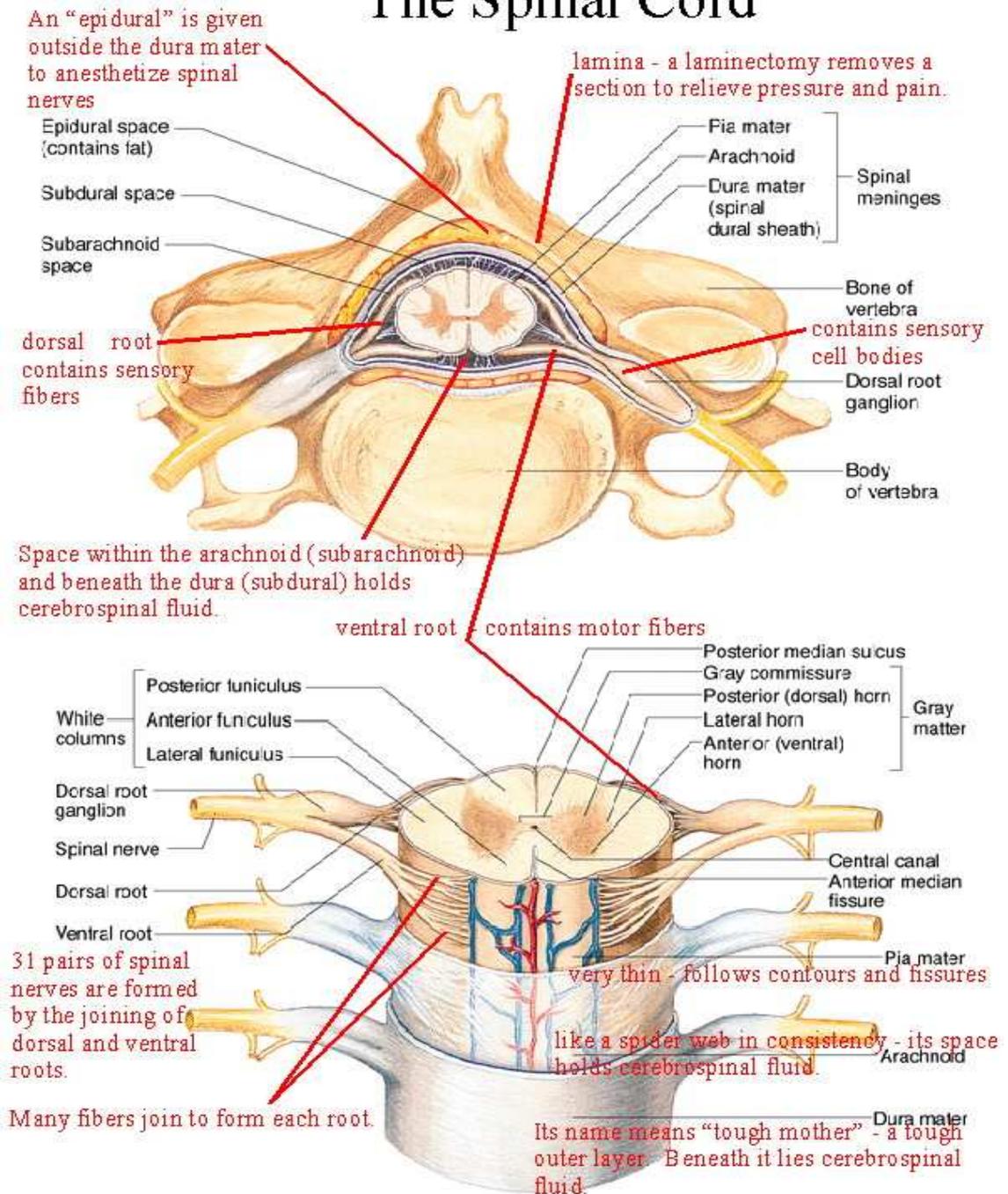


FIGURE 2. The specific details of spinal cord (Swan 2006).

The spinal cord may be damaged in many ways, which produces various symptom patterns. These patterns enable a doctor to determine the location, or the level, of spinal cord damage. The spinal cord can be cut, compressed or destroyed due to an accident or

infection or it could be damaged when its blood supply is cut off or affected by diseases (such as spinal cord cysts, cervical spondylosis, or multiple sclerosis) that alter its nerve function. (Bridwell 2006.)

2.2 International classification of spinal cord injuries

Traditional classification of SCI has the problem of inaccuracy because of not noticing symmetrical motor and sensory functions. For example, if the neurological lesion is in C5, the sensory functions on the right side of the body could be active in dermatome C8 (skin area which is innervated by sensor axons) and motor functions could be active at the level of C7. At the same time, the left side and its sensory functions are active at the level of C7 and motor functions at the level C6. Then neurological functional capacity is much better than so called total C5-tetraplegia. In other words, there are four different segments to be identified in determining the neurological lesion: Right-sensory, Left-sensory, Right-motor and Left-motor. American Spinal Injury Association (ASIA) has published standards for classification of spinal cord injuries (Fig. 3). In these standards, these asymmetrical sensory and motor functions are noticed. (Alaranta et al. 1998.)

Patient Name _____
 Examiner Name _____ Date/Time of Exam _____

ASIA AMERICAN SPINAL INJURY ASSOCIATION **STANDARD NEUROLOGICAL CLASSIFICATION OF SPINAL CORD INJURY** **ISCS**

MOTOR
KEY MUSCLES (testing on reverse side)

R	L		Elbow flexors
			Wrist extensors
			Elbow extensors
			Finger flexors (distal phalanx of middle finger)
			Finger abductors (little finger)

UPPER LIMB TOTAL (MAXIMUM) + =
 (25) (25) (50)

Comments: _____

L2		Hip flexors
L3		Knee extensors
L4		Ankle dorsiflexors
L5		Long toe extensors
S1		Ankle plantar flexors

Voluntary anal contraction (Yes/No)

LOWER LIMB TOTAL (MAXIMUM) + =
 (25) (25) (50)

SENSORY
KEY SENSORY POINTS

0 = absent
1 = impaired
2 = normal
NT = not testable

	R	L	R	L
C2				
C3				
C4				
C5				
C6				
C7				
C8				
T1				
T2				
T3				
T4				
T5				
T6				
T7				
T8				
T9				
T10				
T11				
T12				
L1				
L2				
L3				
L4				
L5				
S1				
S2				
S3				
S4-S5				

TOTALS (MAXIMUM) (50) (50) (50) (50) = _____

Any anal sensation (Yes/No)

PIN PRICK SCORE (max: 112)

LIGHT TOUCH SCORE (max: 112)

NEUROLOGICAL LEVEL: The most caudal segment with normal function

SENSORY	R	L	COMPLETE OR INCOMPLETE? (Incomplete = Any sensory or motor function in S4-S5)	ZONE OF PARTIAL PRESERVATION (Caudal extent of partially innervated segments)	R	L
MOTOR	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
ASIA IMPAIRMENT SCALE	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

• Key Sensory Points

REV-03/06

This form may be copied freely but should not be altered without permission from the American Spinal Injury Association.

FIGURE 3. Standards for Neurological Classification of SCI Worksheet (Dermatomes Chart) (American Spinal Injury Association (ASIA) 2006).

In these standards, motor and sensory level of the lesion of nerve tissue is investigated from left and right side of the body, and whether the lesion is complete or not. The lowest functional sensor segment is the level that has the sense of touch for pin prick and light touch. The lack of the sense of touch, changes in the sense of touch, weakening in the sense of touch and sensitising for the sense of touch are all things that are investigated in these standards. Position sense and deep pressure/deep pain is also examined from all limbs. (Alaranta et al. 1998.) All the key points in each of the 28 dermatomes are studied on the both sides of the body. Ten different myotomes (group of nerve fibers that are innervated by motoneurons) from left and right side of the body are investigated for motor functions. (Maynard et al. 1997.) The lowest motor segment is the level that muscles force is three on the scale of 0-5. In other words, muscles are active and the range of motion is full against gravity. Although above motor segment must be the highest muscle force, five on the scale of 0-5, and full range of motion. The synergy of muscles that affects the movement of joints is investigated in these standards instead of single force produced by one muscle. With these standards, there are classifications for SCI of incomplete (B, C, D) or of complete (A) tetraplegia or paraplegia. (Alaranta et al. 1998.) (Fig. 4).

MUSCLE GRADING

- 0 total paralysis
- 1 palpable or visible contraction
 - 2 active movement, full range of motion, gravity eliminated
 - 3 active movement, full range of motion, against gravity
 - 4 active movement, full range of motion, against gravity and provides some resistance
 - 5 active movement, full range of motion, against gravity and provides normal resistance
- 5* muscle able to exert, in examiner's judgement, sufficient resistance to be considered normal if identifiable inhibiting factors were not present
- NT not testable. Patient unable to reliably exert effort or muscle unavailable for testing due to factors such as immobilization, pain on effort or contracture.

ASIA IMPAIRMENT SCALE

- A = Complete:** No motor or sensory function is preserved in the sacral segments S4-S5.
- B = Incomplete:** Sensory but not motor function is preserved below the neurological level and includes the sacral segments S4-S5.
- C = Incomplete:** Motor function is preserved below the neurological level, and more than half of key muscles below the neurological level have a muscle grade less than 3.
- D = Incomplete:** Motor function is preserved below the neurological level, and at least half of key muscles below the neurological level have a muscle grade of 3 or more.
- E = Normal:** Motor and sensory function are normal.

CLINICAL SYNDROMES (OPTIONAL)

- Central Cord
 Brown-Sequard
 Anterior Cord
 Conus Medullaris
 Cauda Equina

STEPS IN CLASSIFICATION

The following order is recommended in determining the classification of individuals with SCI.

1. Determine sensory levels for right and left sides.
2. Determine motor levels for right and left sides.
Note: in regions where there is no myotome to test, the motor level is presumed to be the same as the sensory level.
3. Determine the single neurological level.
This is the lowest segment where motor and sensory function is normal on both sides, and is the most cephalad of the sensory and motor levels determined in steps 1 and 2.
4. Determine whether the injury is Complete or Incomplete (sacral sparing).
If voluntary anal contraction = No AND all S4-S5 sensory scores = 0 AND any anal sensation = No, then injury is COMPLETE. Otherwise injury is incomplete.

5. Determine ASIA Impairment Scale (AIS) Grade:

Is injury Complete? If YES, AIS=A Record ZPP
(For ZPP record lowest dermatome or myotome on each side with some (non-zero score) preservation)

NO ↓

Is injury motor incomplete?

YES ↓

If NO, AIS=B
(Yes=voluntary anal contraction OR motor function more than three levels below the motor level on a given side.)

Are at least half of the key muscles below the (single) neurological level graded 3 or better?

NO ↓

AIS=C

YES ↓

AIS=D

If sensation and motor function is normal in all segments, AIS=E
Note: AIS E is used in follow up testing when an individual with a documented SCI has recovered normal function. If at initial testing no deficits are found, the individual is neurologically intact; the ASIA Impairment Scale does not apply.

FIGURE 4. Muscle grading and ASIA impairment scale (American Spinal Injury Association 2006).

2.3 Neuromuscular diseases

There are more than 40 different kinds of neuromuscular diseases. Some of the major diseases, which affect the neuromuscular system, are classified into four main groups: motor neuron diseases, neuropathies, neuromuscular junction disorders and myopathies including muscular dystrophies. (Ryöppy 1997.) This introduction concentrates only on those diseases that subjects have and therefore are valid concerning this research paper.

Spina bifida, which literally means “cleft spine,” is characterized by the incomplete development of the brain, spinal cord, and/or meninges (the protective covering around the brain and spinal cord). The human nervous system develops from a small, specialized plate of cells along the back of an embryo. Early in development, the edges of this plate begin to curl up toward each other, creating the neural tube – a narrow sheath that closes to form the brain and spinal cord of the embryo. As development progresses, the top of the tube becomes the brain and the remainder becomes the spinal cord. This process is usually complete by the 26th day of pregnancy. But if problems occur during this process, the result can be brain disorders called neural tube defects. When the process is incomplete on the spinal cord it is called spina bifida. The exact cause of that remains a mystery. Scientists suspect that genetic, nutritional (especially insufficient intake of folic acid) and environmental factors play a role. There is no cure for this disease. There are four different types of spina bifidas. The symptoms of spina bifida vary from person to person depending on which type of spina bifida it is and where the neurological lesion is. (National Institute of Neurological Disorders and Stroke 2005.) In Finland the prevalence of spina bifida was 2,63 / 10 000 births in 2000 (Stakes 2000).

Arthrogryposis multiplex congenita translated from the Greek literally means "curved or hooked joints." Hence, this term is used to describe multiple joint contractures present at birth. There are many causes for congenital multiple joint contractures, and could be due to abnormal nerve or muscle development in the womb. The latter is much rarer. In difficult cases there are variations in every limb and in the mild cases only on the edge of the upper or lower limbs. The cause of arthrogryposis is varied and not entirely understood. Certainly, in many cases abnormal nerve, muscle and connective tissue

development plays a crucial role. Genetic factors do play a part in many cases. (Ryöppy 1997.)

2.4 Physiology of wheelchair racing in athletes with spinal cord injury and diseases

Physical condition and capacity vary with the level of neurological lesion, whether it is incomplete or complete. On one end, there is complete tetraplegia where people are physically disabled and possibly use a respirator. On the other end, there are people with mild paraplegia. These people can even walk by themselves without any devices. There might be other disordered organ systems beside the physical system (genitalia, bladder and intestine problems, spasticity in muscles, autonomic nerves system) or there could be complications (pain, posttraumatic syringomyelia, ossification, osteoporosis, skin problems). (Alaranta et al. 2000.) Wheelchair users usually have a lot of problems with their upper limbs (Dahlberg & Alaranta 1996).

Athletes with SCI or some other neuromuscular disease have unique changes in metabolic, cardiorespiratory, neuromuscular and thermoregulatory systems, which reduce their overall physiological capacity compared with able-bodied athletes or athletes with other types of impairments (Bhambhani 2002). Although respiratory muscle endurance can be increased in competitive athletes with paraplegia by isolated respiratory muscle endurance training (Mueller et al. 2008). During the sprint racing performance, such as the 100 and 200 meter sprints, the primary motor units that will be recruited are the type IIb motor units because they have a fast contractile speed and high glycolytic capacity. The energy for these events will be derived mainly from immediate (adenosine triphosphate ATP and creatine phosphate CP) and short-term (via anaerobic glycolysis) energy sources. (Bhambhani 2002.)

2.5 Classification of athletics in class T54

Discrepancies could arise due to dissimilarities in muscular and/or neural dysfunction. In international competitions athletes with different disabilities are classified according to their individual functional capacities so that they can compete on an equitable basis. Trained classifiers conduct objective tests that involve an examination of the medical records as well as direct observation of the athlete to evaluate the functional capacity

and identify the anatomic level of the lesion. The tests include the evaluation of the trunk and limb movements as well as the strength of specific muscle groups. (International Paralympic Committee 2006.)

In athletics there are events for ambulant and wheelchair athletes in track and field. This study will focus only on wheelchair athletes who are competing in class T54. An athlete who is classified in T54 competes in track event (T) and normally uses a wheelchair. Athlete must meet the conditions for minimal impairment (references to muscle power, joint range of movement, spinal deformity, amputation level and congenital limb shortening, spasticity and tendon reflex changes and limb length differences) to be eligible to compete in International Competitions held under the Rules and Regulations of IPC (International Paralympic Committee) athletics. The functions of upper limbs are normal or almost normal in the class T54. Also the range of trunk function extending is partial or normal trunk function. In this group there may be significant function in lower limbs. (International Paralympic Committee 2006.)

3 WHEELCHAIRS

The wheelchair is the most important thing for its user. To avoid disadvantages caused by incorrect position, the wheelchair is always planned individually and customized for the users purpose. In every sport, there is almost always a specifically designed wheelchair. (Airaksinen & Kataja 1984.) The strength of the upper body, the athletes physical capacity, the level of the neurological lesion and applicability of the wheelchair has to be considered when designing wheelchairs. All above mentioned factors can also affect performance in wheelchair racing. (Masse & Lamontagne 1992.)

Wheelchair racing started at 1948. At that time, the racing wheelchairs were everyday wheelchairs. At first, there were no competition events over 200 meters. (Cooper 1990b.) As the time has passed, the wheelchairs have developed with increasing demands and wheelchair racing performance has improved tremendously over the past years (Table 1). Nowadays **racing wheelchairs** are very light (about 4,5-7,3 kg). Those have three wheels (one wheel in the front and two normal wheels on the back) and monocoque frame which is made of aluminium, titan, chromolly steel etc. (Fig. 5). (Airaksinen & Kataja 1984; MacLeish et al. 1993.) These chairs have tubular tires, precision hubs, large wheels and small pushrims to optimise an individuals racing ability (Cooper 1990b). To enhance the wheeling, racing wheelchairs are built in a more aerodynamic way than everyday wheelchairs (MacLeish et al. 1993).

TABLE 1. Evolution of time for 100 m in Paralympics Games and today's world record (IPC 2008).

Year	Paralympics	Time (s)	Class
1988	Seoul	15,63	A1-3A9L2
1992	Barcelona	14,67	TW4
1996	Atlanta	14,45	T53
2000	Sydney	14,46	T54
2004	Athens	14,3	T54

World record 13,59 sec (22th of May 2008, Ibach, Switzerland)



FIGURE 5. Aero-Racer (Bromakin 2004).

Wheeling feature, stability and applicability to specific sport are very important things concerning the different kinds of wheelchairs used in sports. The frame of the racing wheelchairs should support racers' position in a way that wheeling could be aerodynamic and ergonomic and the trunk could be supported all the time. Wheelchairs should also be quick but at the same time a bit stiff so the transfer of energy to the wheels is more enhanced. (MacLeish et al. 1993.) The relation between center of gravity and adhesion place of the wheels affect the wheeling features as well. When the wheelchair has more weight on the back, it is easier to handle, but on the other hand, it falls back easier. In these wheelchairs, there are short backrests so that the wheeling position is more forward. The disabilities of limbs and differences in racers weight have to be considered when designing racing wheelchairs. (Airaksinen & Kataja 1984.) The size of the frame is determined by the racers size and the stability one wants. The lengthening is useful in racing wheelchairs. Also, the width grows with camber-angle (the angle of wheel and vertical line). (MacLeish et al. 1993.) In general, the camber-angle varies from 5 to 15 degrees. This would prevent the upper arm from abducting in the frontal plane, thus reducing static effort of the shoulder muscles. The effective force vector can also be directed as closely as possible to the shoulder joint. The angle gives elbows a more natural and relaxed way to push the wheelchairs. (Sherill 1993.) The camber-angle affects on the grabbing of the pushrim and therefore has an influence on the duration of pushing and the angular changes in the pushing phase (Ruggies et al. 1994).

The seating position affects the effectiveness of pushing. Masse and Lamontagne (1992) noticed in their studies that seating in middle-low and in behind-low is a little bit

more effective way to push than in front-low, in front-high, in middle-high or in behind-high (Masse & Lamontagne 1992). The researchers have also studied the location of legs. The closer the legs are to the body, the more stable the pushing will be. Their studies also indicate that keeping the knees up will enhance the power of pushing. These results prove what coaches have suggested for years: for athletes with different levels of neurological lesions should have specially designed wheelchairs with different seating positions. Every athlete has to find their own individual and optimistic position. (Ridgway et al. 1988.)

The size of the wheels depends on the racers range of motion of upper limbs, power and the racers experience (MacLeish et al. 1993). The pushrim made of very strong and light material is fastened to the wheels. Very often it is covered with coating tape to enhance the grabbing. There are a lot of different sizes of pushrims. (Airaksinen & Kataja 1984.) The quantities of spokes have to be considered in racing wheelchairs because of the aerodynamics. When the spokes are rolling they mix air and produce turbulences. So reducing the number of spokes will reduce the amount of turbulence. On the other hand, at the same time the power of wheels and stiffness is reduced. This can be compensated with arranging the spokes radially to each other. (MacLeish et al. 1993.)

These are the factors that affect the efficiency of racing wheelchairs in general: weight and balance; frame and wheel stiffness; rolling, bearing and air resistance and the frame geometry (Cooper 1990b). In the other words, **rolling resistance** is one of the major resisting forces. The factors that influence rolling resistance are:

- fixed, customized frame;
- fixed foot/leg support;
- custom-made and tapered front end;
- customized frame angle of 80° or more;
- camber bar;
- fixed backrest;
- fixed clothes protectors;
- weight; as low as possible;
- rear axis: customized seat angle and height; and
- rear wheel camber angle of 6-12°. (van der Woude et al. 2000).

4 BIOMECHANICS OF WHEELCHAIR RACING

Propulsion technique varies between events, between the level of the neurological lesions and between wheelchairs. The movement of upper arms is one of the things that have to be considered when talking about everyday propulsion and wheelchair racing. Many of the top athletes keep their knees as high as they can when propulsing so that air resistance will be smaller. It will also give better position for the upper arms and due to that the body is easier to keep under control. Other option to keep air resistance smaller is to keep the trunk close to knees. (Sherill 1993.) The seat position, pushrim size and variations in terrain could change the propulsion technique (Morrow et al. 2003). There are still few studies done on wheelchair propulsion, especially on racing wheelchair propulsion. One reason for this is that there are a lot of open issues concerning propulsion techniques. Here is a short view on what has been done so far.

There are two different propulsion techniques: semi-circular and circular technique. Short-duration, semi-circular technique is used in wheelchair races on short distances. Upper arms will be pasted by the pushrim and will be released from it in this technique. It is used also in everyday wheelchair propulsion. Long-duration, circular technique is used in longer distances. In that technique the upper arms will follow the pushrim all the time and grip will never be released. It only will be loosen at the end of the propulsion. (Sherill 1993.) With this technique, racers can keep their velocity as high as they can and the velocity is also stable. This technique requires good physical condition and smaller pushrims than normal propulsion technique. Both upper arms must do the propulsion at the same time with the same amount of force to keep the propulsion in balance. (Airaksinen & Kataja 1984.) There is also discussion about the differences between the conventional (CVT, also called thumb-technique) and para-backhand (PBT) propulsion techniques in literature. With the CVT, the hands are fully flexed in a tight fist with the thumb in a slightly extended position. The contact of the pushrim occurs between the first joint and the knuckle of the thumb. A flick of the wrist is commonly observed at the bottom of the stroke. CVT- technique demands impaired upper extremity function. Using a specialized glove designed for the PBT, the hand makes initial contact with the pushrim with the back of the index and middle fingers between the first and second joints rather than the thumb. This technique is popular

among racing wheelchair athletes with upper extremity injuries. (Chow et al. 2001.) In general one might generalize the propulsion technique as a push and pull technique which is used for standard wheelchairs (Sanderson & Sommer 1985), whereas the racing propulsion technique is referred to as a punching of the pushrim technique (Cooper 1992).

4.1 Different phases in wheelchair propulsion

Wheelchair propulsion can be divided into two phases: propulsive phase and the recovery phase. During the propulsive phase, hands are in contact with the pushrim so that the muscle force maintains or increases the velocity of the wheelchair. Propulsive phase typically starts when hands grasp the pushrim near or behind top dead center, TDC. This phase will end when hands are released from the pushrim. In the recovery phase, hands are released from the pushrim and the grip is taken again and a new propulsive phase begins. In theory this happens, but compared to circular technique, it is not so obvious or visible every time. (Sanderson & Sommer 1985.)

Cooper (1995) has divided entire arm pattern during propulsion into five categories: (a) The elbows are in the highest position where arms are pointing forward and downward (Component 1), (b) starting the propulsive phase (Component 2), (c) hand on pushrim (Component 3), (d) end of the propulsive phase, “flick” (Component 4) and (e) the elbows are driving to top (Component 5) (O’Connor et al. 1998) (Fig. 6).

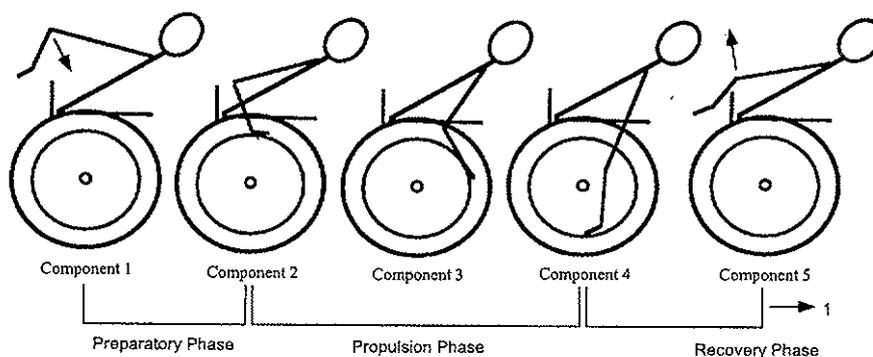


FIGURE 6: The five categories of wheelchair propulsion (O’Connor et al. 1998).

4.2 Kinematic variables in wheelchair propulsion

Many studies have examined kinematic features of wheelchair propulsion. The biomechanical variables investigated in these studies are the movement of the wheelchair propulsion and the movement of the segments of body, (handling in chapter 4.3.), cycle frequency, push and recovery time, the linear velocity of shoulder, elbow and wrist and their angular kinematics and start and end angle of propulsion. (O'Connor et al. 1998; Sanderson & Sommer 1985; Vanlandewijck et al. 1994; Wang et al. 1995.)

Cycle frequency is the amount of full cycles per time. The changes in speed will cause changes in cycle frequency and in the interrelation of push time (time spent on the propulsive phase) and recovery time (time spent on the recovery phase). At the same speed, a higher body mass leads to higher cycle frequency because of the greater workload. (Veeger et al. 1989.)

Push and recovery time are often measured in wheelchair studies. The time spent in one whole cycle, cycle time, can be calculated with these times. In Lamontagne's (1981) studies the push time was consistent in different velocities and seating positions. Push time was around 38 % of the whole cycle. In Cooper's (1990a) studies push time was on average 33 % of the whole cycle and recovery time was on average around 67 % of the whole cycle in different distances. When the recovery time gets shorter it limits the backward movement of body. It also has an influence on acceleration, because of the negative impact of the impulse produced by hands to the pushrim. (Wang et al. 1995.) So when the push time shortens also the breaking forces (the inertia of the athlete, the rolling resistance of the wheel etc.) diminish. On the other hand, so much impulse cannot be produced at that time. (Cooper 1990a; O'Connor et al. 1998.) It is very relevant for wheelchair racing that push time is the same for every cycle and, at the same time, push angle will not change when maintaining the speed (Wang et al. 1995).

O'Connor et al. (1998) studied the velocity of a wrist in contact with the pushrim and the velocity of an elbow. The velocity of the wrist in the beginning of the propulsive phase, which transfers the speed to the pushrim at the same time, is in a major role in measuring the velocity of the wheelchair. The velocity of the elbow is in a major role in preparing the thoracic muscle for effective propulsion. If the push time gets longer and

the velocity of the wrist diminishes, it might cause ineffective propulsion. (Cooper 1990a; O'Connor et al. 1998.) With the maximal linear velocity of the shoulder and elbow in the start of propulsive phase, and the maximal linear velocity of hand (flick of hand at the end of the propulsive phase / at the beginning of the recovery phase) will ensure the maximal velocity of the wheelchair. The linear velocity of the hand has to be equal or bigger than the velocity of the pushrim. Otherwise the hand will reduce the velocity of the pushrim. (Wang et al. 1995). Also grasping the pushrim will have the same negative effect on the velocity of the wheelchair (Cooper 1990a).

The angular changes have also been studied. Ridgway et al. (1988) have done a research studying the kinematic features of 800 meter wheelchair racers. They studied the angular changes between head, arm, elbow, trunk and legs while propulsion. Also Lamontagne (1981) has done a study about these same parameters. The angular kinematics of elbow varied in every velocity and seating position. They noticed that when legs were higher, the angle between legs and lower body was 30 degrees, the relative amplitude of elbow angle was lower than when the angle was 90 degrees. When measuring the same propulsion phase, the angle of elbow was bigger in 90 degrees seating position than in 30 degrees seating position (Fig. 7). In the same study, they noticed that the stability of subjects upper body (only one subject has paraplegia) was better in high velocity than in low velocity. This was because the movement of upper body was shorter in high velocity than when the velocity was decreasing. (Lamontagne 1981.)

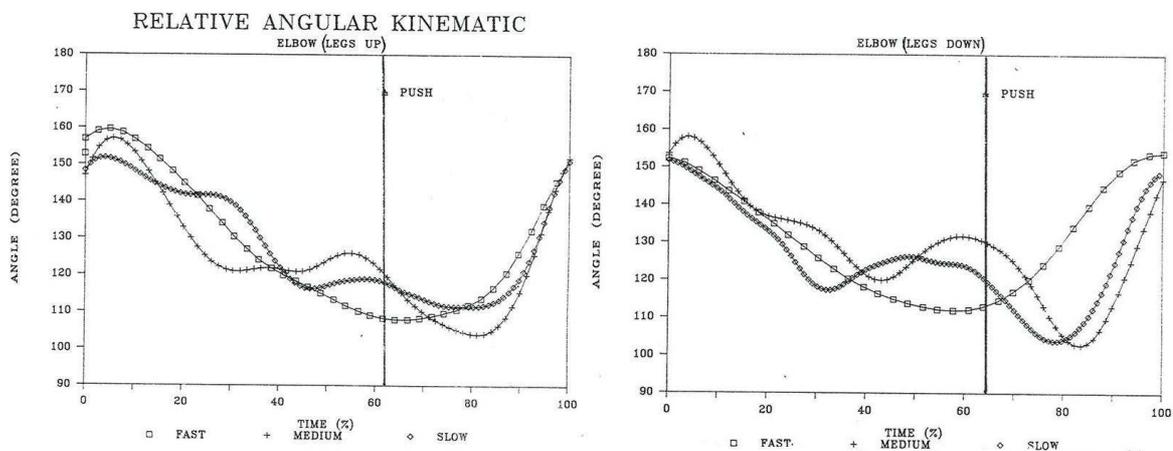


FIGURE 7. A comparison of the angular displacement of the elbow a) for the legs up position and Bb) for the legs down position at three spinning speeds (Lamontagne 1981).

O'Connor et al. (1998) perceived that the angle of elbow increased with speeding. This might be an explanation for athletes to move their body upward, in vertical direction, so they have time to get the body downward when hands are preparing to be in contact with pushrim. This helps racers to use their own mass of body and gravity to enhance power and improve the technique of propulsion. When hands are in contact with the pushrim, the smaller elbow angle helps racers to stabilize their arms. This is because of elbows bend more and arms are now closer to the body. Then athlete can produce higher impulse to the pushrim and the stability of shoulder increases. Smaller elbow angle indicates that the point hands are contacting the pushrim is closer to the shoulder joint, which decreases the moment arm around the shoulder joint. This smaller moment arm reduces the load of the shoulder joint and therefore it is possible to reduce the general problem with wheelchair athletes shoulders. (O'Connor et al. 1998.)

In general, the start angle, the end angle and relative differences of the push angle are studied (Dallmeijer et al. 1998; Wang et al. 1995). Wang et al. (1995) noticed that having effective propulsion enables the racer to retain the same push angle when speeding and at the same time, racer have to do the propulsive phase quicker than the recovery phase.

4.3 Muscles and movement patterns in wheelchair propulsion

Here is a short review for muscles and movement patterns used in wheelchair propulsion. It helps to understand more about wheelchair propulsion even though muscles at work were not measured in this study.

The force for propulsion depends on many things such as the features of the wheelchair, seating position and its relation with the hub of the wheel, the size of the diameter of the pushrim and camber angle (van der Helm & Veeger 1996). The muscles and joints of the shoulder, elbow and wrist are active when producing the force and power to propulsion (Ruggles et al. 1994). Rodgers et al. (1994) studied more specifically about the muscles involved in propulsion. They perceived in EMG-studies that m. biceps brachii is active in the beginning of the propulsive phase and at the very end of the recovery phase (in exhaustion). This muscle works as a flexor of the arm in the beginning of the propulsive phase and at the phase where one puts hands on the

pushrim. M. triceps brachii is active in the recovery phase when the push and pull movement is seen between the action of m. biceps brachii and m. triceps brachii. Most of the time of the propulsive phase m. deltoideus anterior is active in the flexion of the shoulder and in the recovery phase. M. deltoideus posterior is active in the extension of the propulsive phase and in the beginning of the recovery phase. M. flexor carpi ulnaris and m. extensor carpi radialis are both active in most of the time in propulsive phase, which provide a more rigid member for the transfer of forces. (Rodgers et al. 1994.) Also m. infraspinatus and m. supraspinatus participate in propulsion (van der Helm & Veeger 1996). On the other hand, when Chow et al. (2001) examined the differences in electromyography (EMG) between two racing wheelchair propulsion techniques they got partially different results (Fig. 8).

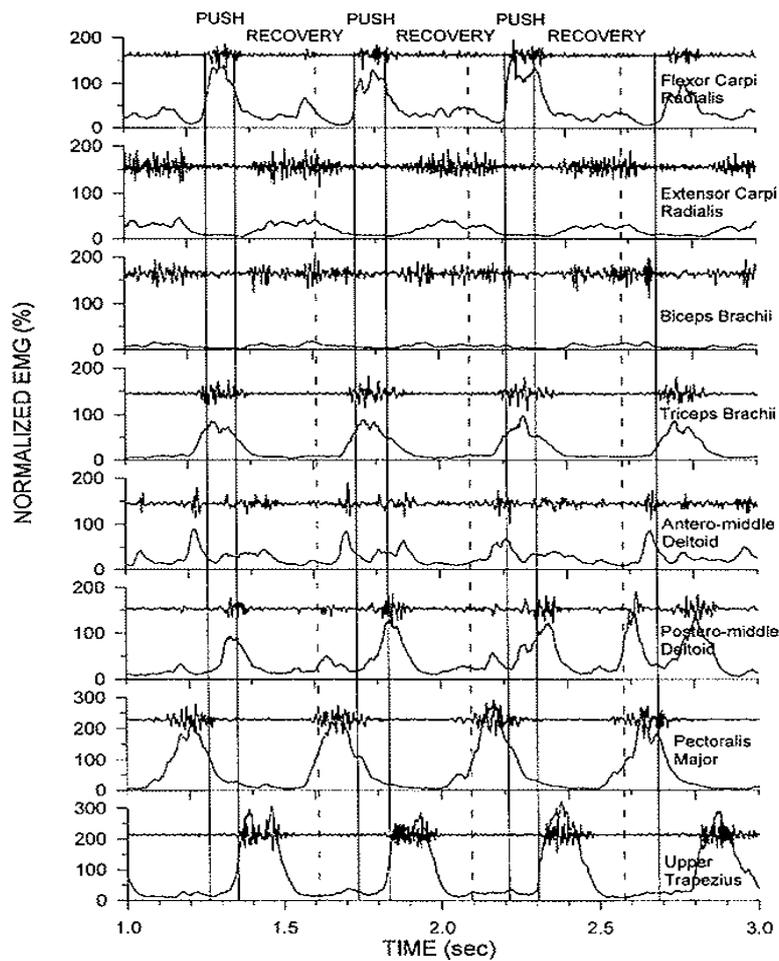


FIGURE 8. Raw and normalized EMG of different muscles for a conventional (CVT) subject. The vertical lined indicate instants of hand contact and release, (solid lines) and maximum elbow height (dashed lines). (Choe et al. 2001.)

Cerquiglini et al. (1981) defined that the muscles of elbow do one third of the whole propulsion, the muscles of wrist one fifth and the muscles of shoulder do the rest. The muscles of wrist do isometric work in the beginning of the propulsion and eccentric work at the end of the propulsion. The muscles of elbow are first doing concentric work that is followed by isometric phase and an eccentric phase. The most of the propulsion phase is caused by m. deltoideus anterior and m. pectoralis major. The force is never more than 20 % of maximal force according to their investigations. (Cerquiglini et al. 1981.)

In the beginning of the propulsion phase the elbow is actively flexed: after this the shoulder abducts, the shoulder lifts (because of m. trapezius) and the shoulder blade rotates (Cerquiglini et al. 1981). The rotating of shoulder blade depends on the size of the pushrim, its orientation and the racers force. Also the size of the pushrim has an influence on the movement of the body while propulsion. (Hughes et al. 1992.) Also Veeger et al. (1991) have got the same results that the smaller pushrim is more favourable in fast and low-intensity distances. This can be seen in the racing wheelchairs. (Veeger et al. 1991.) Hughes et al. (1992) stated that the movement of the joints depends on seating position while propulsion.

There are two phenomena in propulsion that affect its effectiveness and load. These two are the stability of glenohumeral joint and the kinematics movement. Isometric and eccentric contracting muscles, which are activated in stabilization, produce metabolic energy. At this time they do not produce outside force. Muscles produce positive force only when muscles are under concentric work. So stabilization enquires force, which could be a part of the reason that propulsion is ineffective. The movement should be tangential to pushrim. Then the joint of shoulder and elbow are straightened out and at the same time flexing momentum must be present for the result to be ideal. (van der Helm & Veeger 1996; Roelevald et al. 1994.) Goosey-Tolfrey et al. (2001) investigated the nature of the pushrim forces during the propulsion of a racing wheelchair. They noticed that the peak forces occur at an angle between 140° and 180° in the racing chairs contrast to the peak approximately 30° in everyday chairs. Racers were accommodating the forces with increasing speed, not changing the propulsion strategy. (Goosey-Tolfrey et al. 2001.)

The forward movement of the body depends on effective propulsion. The further the racer leans forward, the more power the racer produces to pushrim. Producing force composes of three things: gravitation, the acceleration of the movement when body leans backward and abdominal (which are functional) activity. (Sanderson & Sommer 1985; Veeger et al. 1989.) Ridgway et al. (1988) have got the same results. Wang et al. (1995) noticed that the flexion of body is bigger in high velocities than in low velocities. This was caused of bigger start angle and bigger angle of elbow in the beginning of the propulsive phase. When the body moves forward and backward, a part of the weight of it may shift through the joint of shoulder and elbow to hands. The flexion of body may cause better acceleration of pushrim in the beginning of the propulsion. The wide vertical movement of abduction and hyperextension of shoulder in the recovery phase is one way to get to the maximal speed. (Wang et al. 1995.) There were not found any studies that studied the muscles of body during the propulsion.

Production of force is affected by the position of head and its movement while propulsion and before that. Just before propulsion the flexion of head can produce more force, which transfers to body, then continues to hands and onwards to pushrim. The extension of head happens in the end of the propulsive phase. With all these factors put together, the racer is more streamlined and air resistance diminishes. (Ridgway et al. 1988.)

5 THE PURPOSE OF THE STUDY

The level of neurological lesion, the neuromuscular disease and the features of the wheelchair play all an important role for determining the kinematics variables in wheelchair propulsion. The performances of the wheelchair athletes have continually enhanced during past years. One way to succeed in wheelchair racing is trying to improve the start technique. Few studies have analyzed the kinematic variables in wheelchair racing propulsion (Chow et al. 2001; Higgs 1986; O'Connor et al. 1998; Ridgway et al. 1988; Wang et al. 1995) but there are only two published articles about the kinematic variables in the sprint start of wheelchair racing (Moss et al. 2005; Tupling et al. 1986). The purpose of this study was to examine kinematic differences between wheelchair racers (T54) in sprint start.

The following problems can be drawn from the purpose:

1. Are there any differences in time variables during the first and the third push at start between the athletes?
2. Are there any differences in angle variables during the propulsive and the recovery phase at start between the athletes? How the angle variables affect on movement patterns of body and on movement patterns of segments of their body at start?
3. Are there any differences in the velocity of wrist and elbow in different phases of the cycle and in different pushes at start between the athletes?
4. What kind of different starting positions athletes have?

6 METHODS

6.1 Subjects

Three male elite disabled athletes, aged 21-25 (mean 23,3 years) participated in this study. All of them were international level wheelchair racers, paralympic gold medallists, and competing in the class T54. They were participating in the Paralympic Wheelchair Training Camp in Kuortane Training Center and all racers had experience in wheelchair racing (mean 6,7 years). Table 2 shows the personal data. They were fully informed of the procedures and the risks involved in this study and they gave their informed consent (Attachment 1). They were also allowed to withdraw from the measurements at will.

TABLE 2. Personal data of the subjects.

Subjects	A	B	C	Mean
Age	21	24	25	23,3
Weight (kg)	59	63	48	56,7
Height (cm)	153	175	145	157,7
Years in wheelchair	21	7	25	17,7
Diameter of pushrim (cm)	37,2	38	38	37,7
Diameter of wheel (inch)	28	28	28	28,0
Years of racing	5	7	8	6,7
Disability	Spina Bifida	Artrogryposis Multiplex Congevit	Spina Bifida	
Racing position	Seated	Kneeling	Kneeling	

6.2 Procedures

Before starting the protocol each racer did warm-up independently. Athletes used their own racing wheelchairs (mean diameter of the wheel 28 inch, mean diameter of the pushrim 37,7 cm) and regular racing equipments (gloves, leg restraints). The athletes were allowed to use their own racing wheelchairs in order to acquire their natural

technique of the racing wheelchair propulsion and to provide to most accurate data representing their racing wheelchair start technique. All the racing wheelchairs were high quality so it was hypothesized that there were no significant advantage to any participant. The filmed distance was 10 m. Athletes did maximum performances (100 % of Max) four times, 80 % of maximum (80 % of Max) and 60 % of maximum (60 % of Max) two times. Totally there were eight performances of each athlete. From 3 to 5 min rest periods were allowed between trials to minimise the effect of fatigue. Athletes were advised to focus to each performance as a competition. Starting commands used in athletics were employed to initiate each of the sprint trials. The lower speeds (80 % Max and 60 % Max) were so artificial simulations of the wheelchair propulsion that they did not give any valid data for optimising the maximal start, for that reasons those results are not under the main observation.

6.3 Apparatus

The kinematic data were collected using video recording and then digitised using a motion analysis system (Peak Motus 8.5, Peak performance Inc., Denver, Colorado, USA). This two-dimensional motion analysis was made by using High Speed Digital Imaging system with two high-speed-cameras (MotionScope 1000SC, Redlake MASD, Inc., USA) next to each one. Figure 9 shows that Camera #1 was set 27 m in front of the propulsion line and it filmed from start to 5 m. Camera #2 was placed with the same standards than Camera #1 from 4 m to 10 m. The time was measured by using two beam sensors (SUN X, Beam Sensor VF2-RM5, Japan) at the start and at the end. There were two extra lights (IANIRO 800, Italy) enhancing reflections of the markers. The test was made on the track and field surface (Novotan CC). Film rate was 250 frames per second. The arm movements of these athletes during the propulsion phase were hypothesized to be bilaterally symmetrical. Thus only there were two cameras positioned 27 m from the subject so that the axis of the lens was orthogonal to the subject's sagittal plane. It was assumed that because of this symmetry of motion there would be negligible or no rotation of the trunk about its longitudinal axis (Goosey & Campbell 1998). The calibration frame was filmed prior the tests.

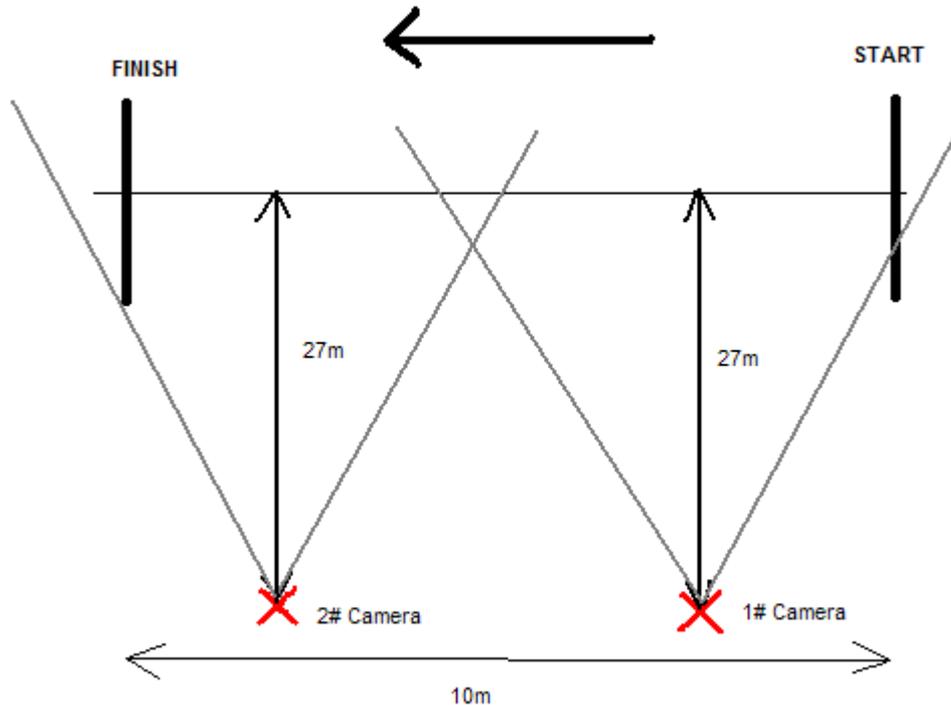


FIGURE 9. Exciperimental set up

Nine reflective markers were placed on the left side of the participants: top of the head, in front of the ear, on the shoulder (ligament Acromio-clavicular), on the elbow (epicondylus lateralis), on the wrist (processus styloideus ulnae), on the hand (third metacarpal), and on the knee (the proximal point of Patella). Also, markers were placed on the hubs of the rear and front wheel (Fig. 10).

Acceleration sensor was placed on the frame of back of the wheelchair (Muscle Tester ME3000 Professional: Mega Electronics, Kuopio, Finland). The speed of the wheelchair was measured with speed radar (LAVEG, jenoptik).

6.4 Analysis

The fastest trial (100 % of Max) and the closest trial to the 80% of Max and 60% of Max were manually digitised using motion analysis software (Peak Motus 8.5 Peak performance Inc., Denver, Colorado, USA). The raw co-ordinate data were transformed and the data were smoothed with a Butterworth filter with cut-off frequency 20 Hz. The timing parameters; cycle time (time spent on one cycle), push time (% of the cycle time,

s) and recovery time (% of the cycle time, s) were calculated. Push time was defined as the time during which the hand was in contact with the pushrim. Recovery time was defined as the time when the hand was not in contact with the pushrim.

The resultant velocities analyzed were: 1) the velocity of the wheelchair in the first and third cycles in the 100 % of Max, 2) the wrist velocity in the max performance in the end of the first, second and third cycle, 3) the elbow velocity in the Max performance in the beginning of the propulsive phase on the second, third and fourth cycle, 4) the elbow velocity during the propulsion and the recovery phase on the maximum trial and on the third cycle. The resultant velocities were calculated according to:

$$\Delta v_r = \sqrt{(\Delta v_v^2 + \Delta v_h^2)},$$

where Δv_v = vertical velocity, Δv_h = horizontal velocity.

The following two angular variables were analyzed of the first and third cycles in the 100 % of Max, of third cycle in 80 % of Max and of 60 % of Max according to:

$$\Delta \alpha = \text{degrees}(\text{atan}((y_2 - y_1) / (x_2 - x_1))).$$

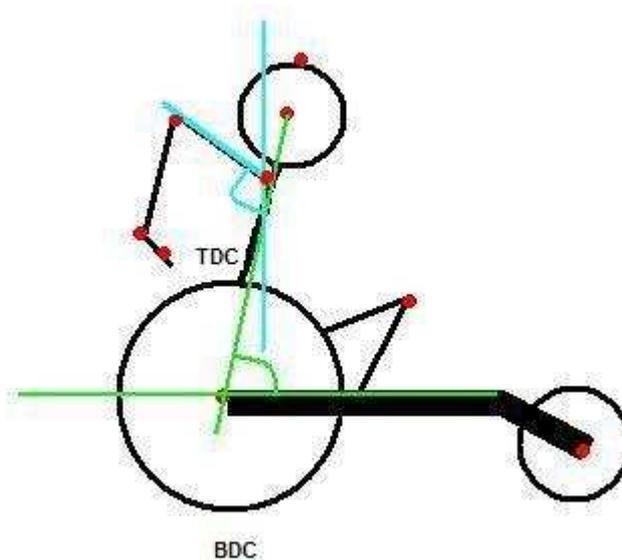


FIGURE 10: Angular parameters that were analyzed were trunk angle (green angle) and shoulder angle (blue angle). Also the nine reflective markers are shown in this figure.

The angles were defined as follows: shoulder angle (formed by a line from the elbow to the shoulder with the vertical) and trunk angle. To estimate the motion of the trunk, the trunk angle was measured by forming the front of the ear marker, the rear wheel hub marker translated along the x-axis. This variation only approximated motion of the trunk due to number of factors. The motion described was not a true trunk rotation because the subjects actually flexed in the mid-trunk region. The seat cage provided support and stabilization and determined body position with respect to the pushrims for the athlete, but the seat cage also imposed to see where the hip was. So the rear wheel hub marker was used in these measurements. Also the angular velocities of trunk were measured. Contact angle (CA) and range of push angle (RPA) were analyzed using the data from wrist and rear wheel hub marker and their relation to vertical line (TDC or BDC) (Fig. 11).

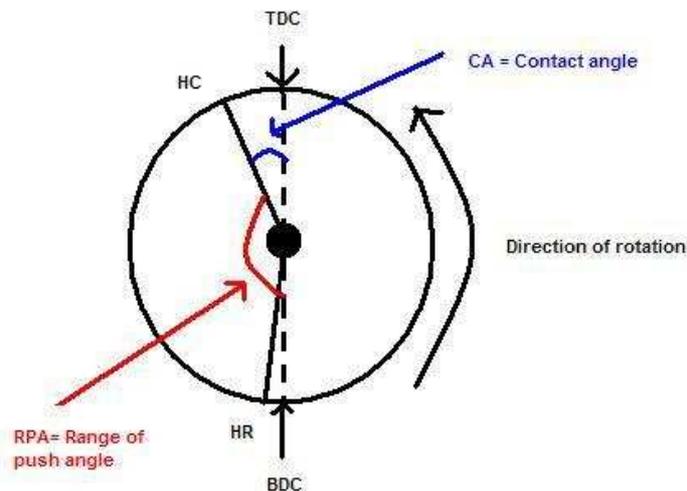


FIGURE 11: Angular parameters (CA and RPA) used to indicate the locations of the hand relative to the wheel center at the instants of initial hand contact (HC) and release (HR).

The point of contact (cm from TDC) and release (cm from BDC) during the propulsive phase of the stroke cycle were also examined.

6.5 Statistics

In some cases, average and standard deviation were calculated for some of the relevant variables. However, due to nature of this study no other statistics analyses were performed.

7 RESULTS

7.1 Timing parameters

The absolute and relative data for the push time and recovery time during the first and third cycles in maximal performances, and the duration of each cycle, are presented in the Table 3. The mean push time for the first push at maximum start was 0,60 s and for third push 0,23 s. Recovery time was 0,15 s and 0,21 s on average in the same performances. When speed increased, the propulsion phase was performed faster while the recovery phase increased on subject A and C and decreased on subject B. As predicted, the cycle time decreased as the speed increased on all athletes. Subject A had a much faster first cycle than the other subjects but the advantage was vanished when the third cycle was performed.

TABLE 3. Starting position and timing parameters in the performances.

Subject	Performance	Push Time (s)	Recovery Time (s)	Cycle time (s)
A	100 / 1	0,4	0,136	0,536
	% cycle time	75	25	
	100 / 3	0,228	0,252	0,48
	% cycle time	47,50	52,5	
B	100 / 1	0,66	0,184	0,844
	% cycle time	78	22	
	100 / 3	0,188	0,152	0,34
	% cycle time	55	45	
C	100 / 1	0,752	0,212	0,964
	% cycle time	78	22	
	100 / 3	0,26	0,224	0,484
	% cycle time	54	46	

100 / 1= Maximun trial / First push, 100 / 3= Maximum trial / Third push

The mean percentages of the propulsion phase and the recovery phase are presented in Figure 12. The data indicated that in the beginning the differences between these phases were enormous but it was almost even on the third cycle on the maximum trial (Fig. 12).

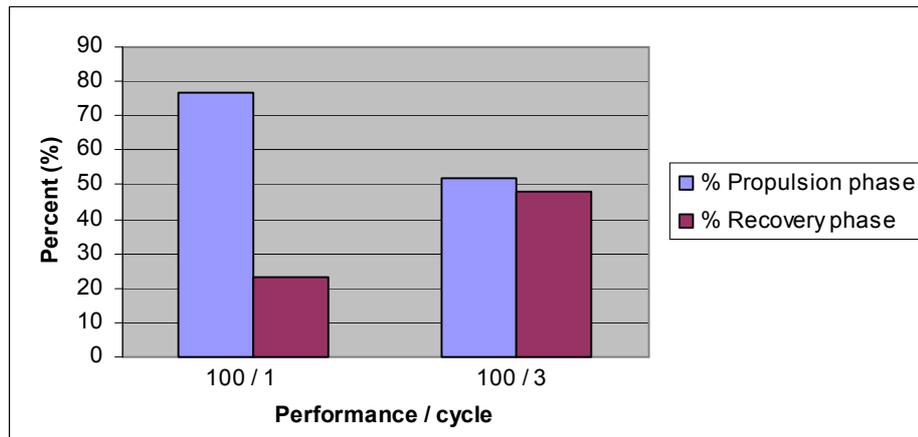
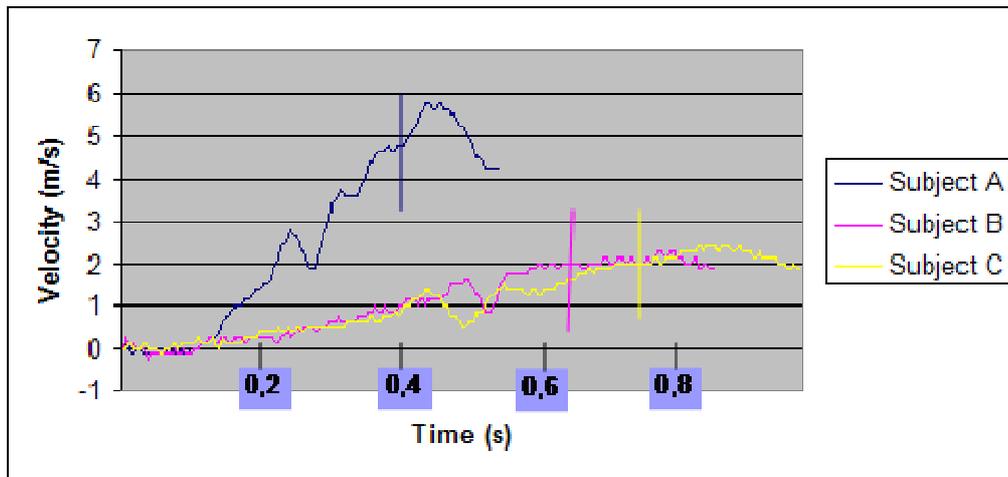


FIGURE 12: The average relative data of the propulsion and the recovery phase of the subjects in the first and third cycles. 100 / 1 = Maximum trial / First push, 100 / 3 = Maximum trial / Third push.

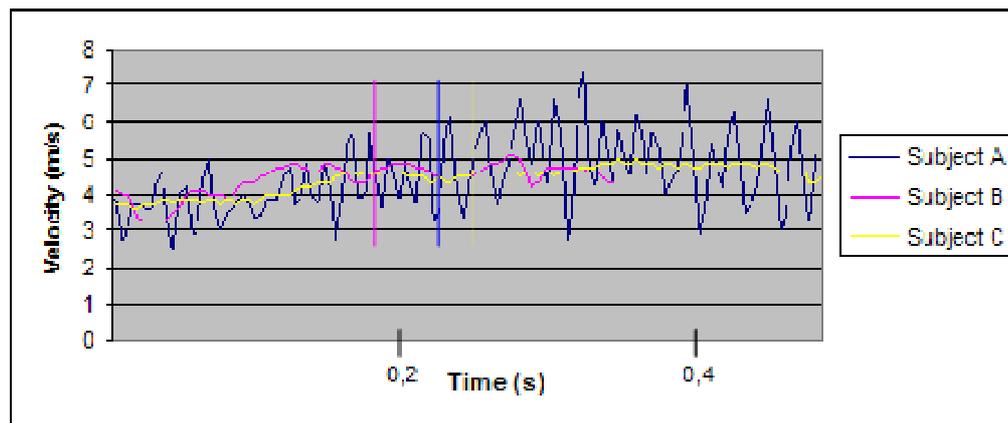
The time for 10 m was measured by using two beam sensors and for the 100 % Max the times were 2,39 s, 2,36 s and 2,51 s for subject A, B and C respectively.

7.2 Linear velocities

Figure 13 allowed the comparison of the wheelchair velocities of each subject during the first and third cycle in maximal start. During the first cycle the velocity of the wheelchair was much faster on the subject who was seated but subjects having other seating positions caught up with the subject A during the third cycle. Subject A had very variable velocity of the wheelchair during the third cycle. The mean wheelchair velocity during the first cycle was 2,63 m/s, 1,07 m/s and 1,14 m/s for subject A, B and C respectively. For the third cycle the same values were 4,53 m/s, 4,43 m/s and 4,44 m/s.



a)



b)

FIGURE 13. The wheelchair velocity of the first (a) and third (b) cycle on the Max. The vertical lines reflect the change from the propulsion phase to the recovery phase.

Wrist velocity in the Max performance in the end of the first, second and third cycles are demonstrated on Figure 14. Subject A had the maximum wrist velocity, 2, 24 m/s, in the end of the third recovery phase.

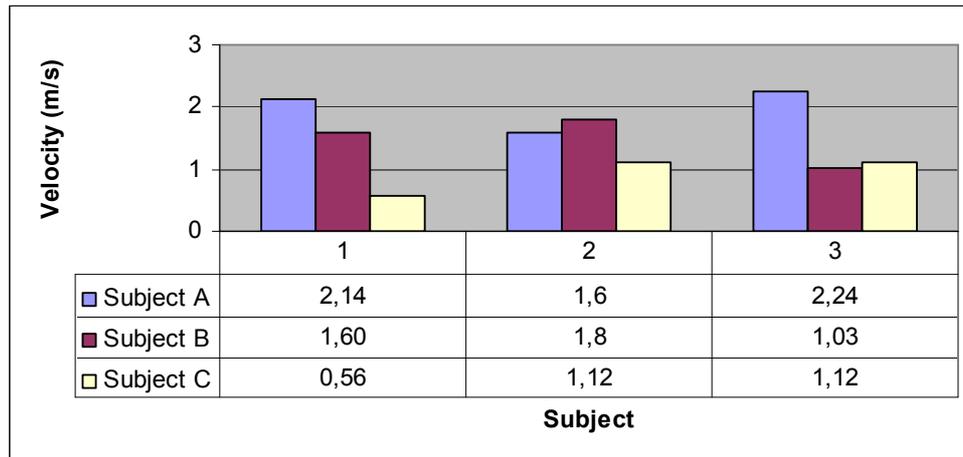


FIGURE 14. Wrist velocity in the max performance in the end of the recovery phase of the first (1), second (2) and third (3) pushes.

The values for elbow velocity in the Max performance in the beginning of the propulsive phase on the second, third and fourth cycle showed that subject A had the maximum elbow velocity, 2,26 m/s, in the beginning of the second propulsive phase (Fig. 15).

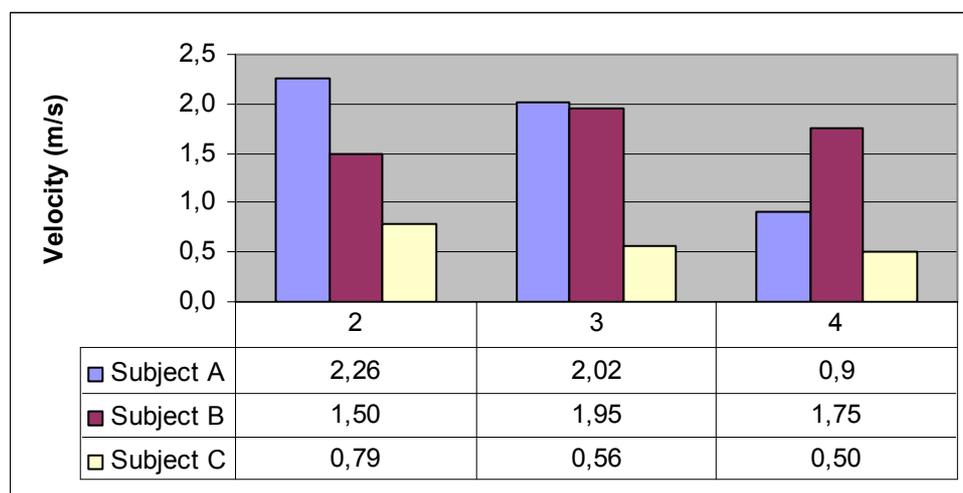
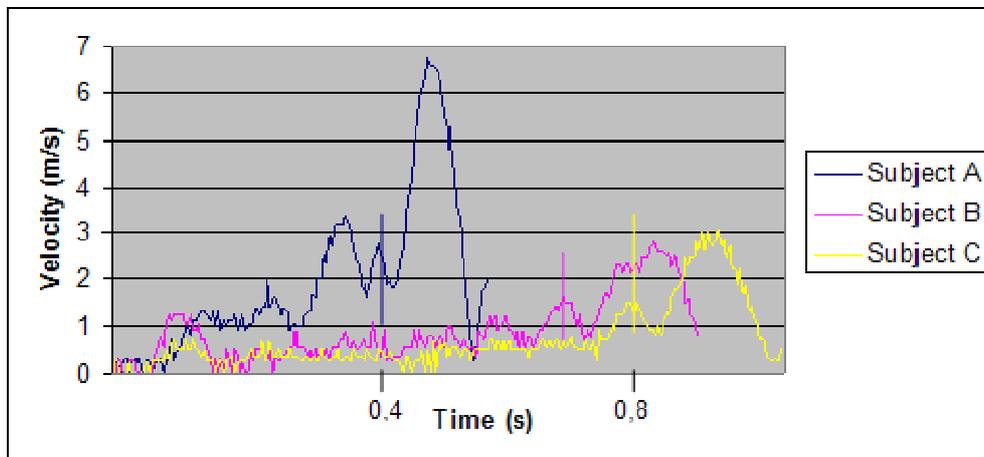


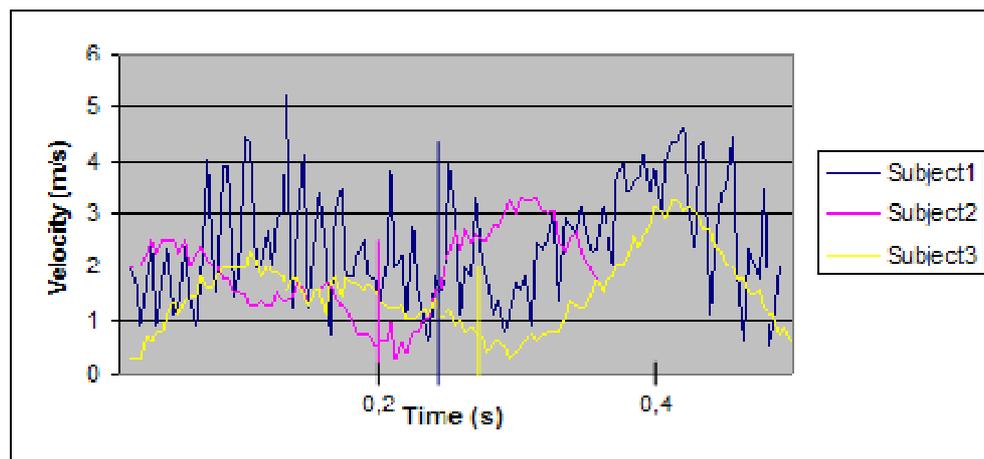
FIGURE 15. Elbow velocity in the Max performance in the beginning of the propulsive phase on the second, third and fourth cycle.

The elbow velocities on the maximal start are demonstrated in Figure 16. Again the subject A had greater velocities than the others but it seemed to smoothen when reaching the third cycle. The mean elbow velocity on the first cycle was 1,94 m/s, 0,90

m/s and 0,72 m/s for subject A, B and C respectively. For the third cycle the same values were 2,42 m/s, 1,89 m/s and 1,51 m/s.



a)



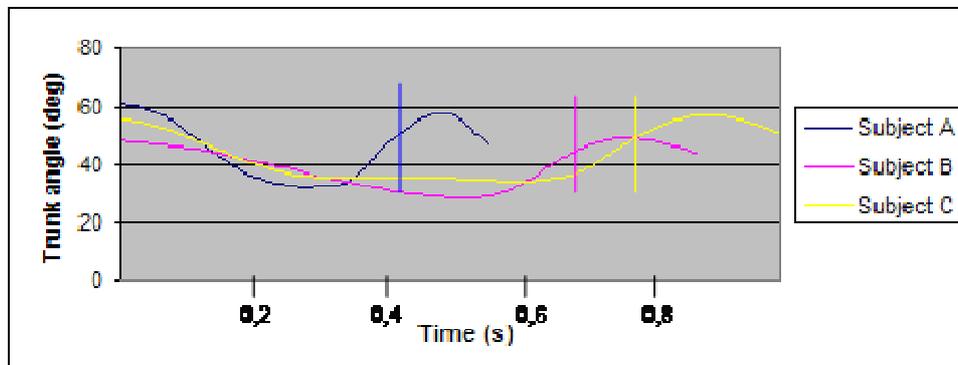
b)

FIGURE 16. The elbow velocity of the first (a) and third (b) cycle on the Max. The vertical lines reflect the change from the propulsion phase to the recovery phase.

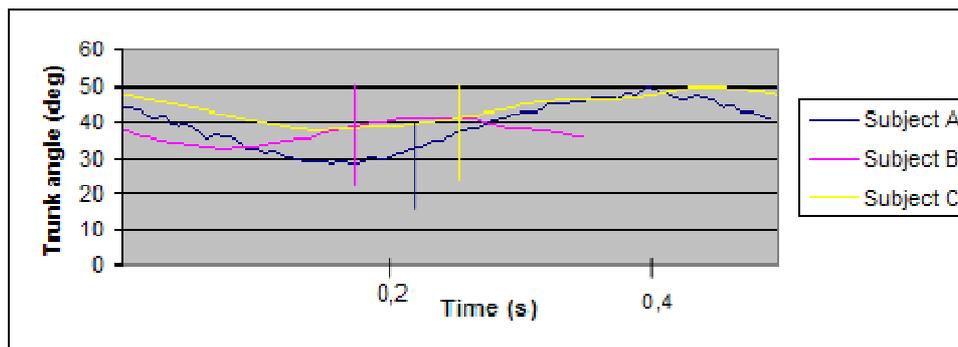
7.3 Angular variables and movement patterns

All subjects showed decreases in the changes of trunk angle, when velocity increased during the start phase. Subject A had more changes in trunk angles (more trunk motion) than other subjects and it should be noticed that the start position of subject A demanded a larger start angle of the trunk (Fig. 17a). At start position, the angle varied from $48,2^\circ$ to $60,9^\circ$. In the beginning of the propulsion phase the trunk angle decreased

but in some point of the propulsion phase trunk appeared to prepare for the recovery phase with increasing the trunk angle to the end of the propulsion phase. The trunk motion was smaller on the third cycle than on the first cycle.



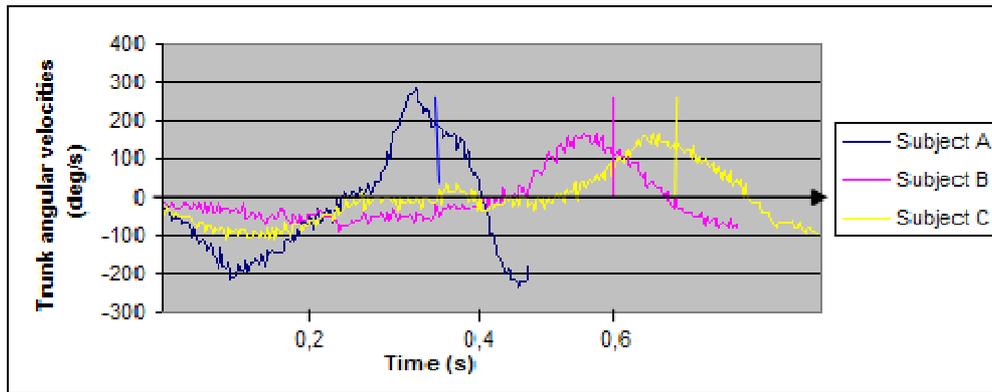
a)



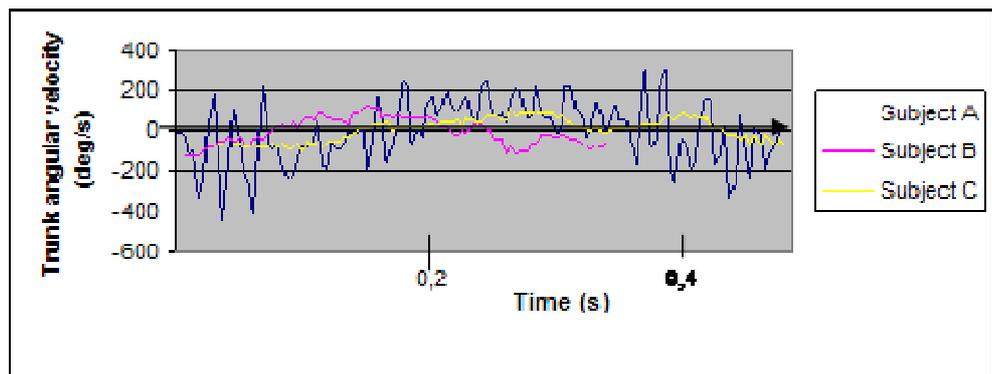
b)

FIGURE 17. Trunk angle of the first (a) and third (b) cycle on the Max. The vertical lines reflect the change from the propulsion phase to the recovery phase.

The angular velocities of the trunk in maximum trials are illustrated in Figure 18. All subjects had their maximum angular velocities of trunk just before the recovery phase. Subject A had greater values than others.



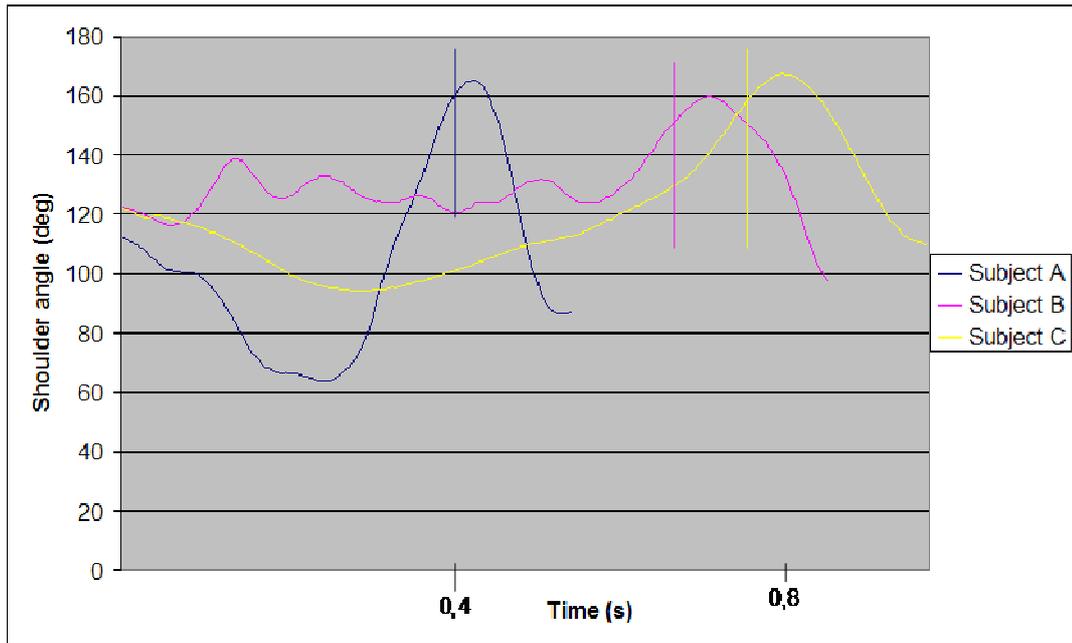
a)



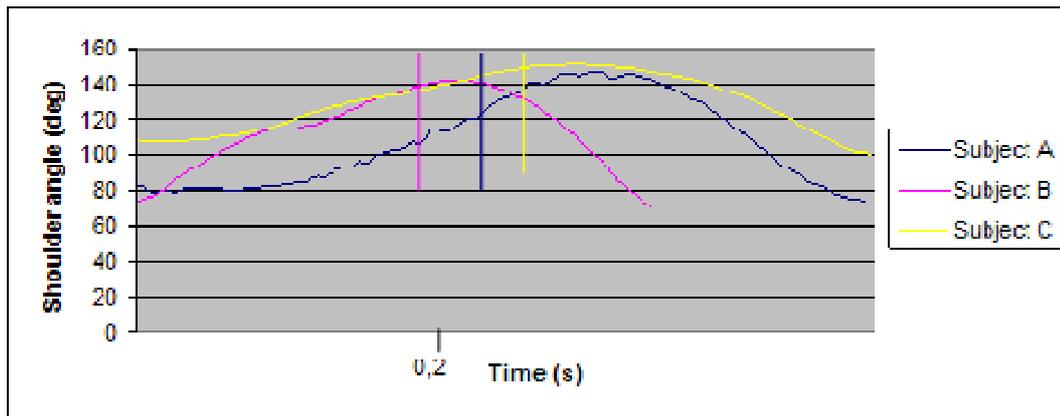
b)

FIGURE 18: The Trunk angular velocities in the first (a) and in the third (b) cycle in Maximum trial. The vertical lines reflect the change from the propulsion phase to the recovery phase.

All the subjects had almost the same kind of shoulder angle at the start. The maximum shoulder angle appeared to be just in the beginning of the recovery phase in all athletes. The shoulder angle changes were the largest on the subject A (Fig. 19a). Few pushes after, the changes in shoulder angle were smoothed. On the third cycle, the changes between athletes were smaller than on the first cycle. Subject B had the largest changes on shoulder angle on the third cycle (Fig. 19b).



a)



b)

FIGURE 19. Shoulder angle of the first (a) and third (b) cycle on the Max. The vertical lines reflect the change from the propulsion phase to the recovery phase.

The initial contact angle and the ranges of the wrist push angles in the three speed conditions are presented in Table 4. The mean contact angle at maximum start was $34,7^\circ$ and on the third cycle $12,0^\circ$. Subject C had the smallest contact angles. In other words subject C started the propulsion phase closest to the TDC.

TABLE 4. Contact angle and range of push angle of the trials

Contact angle (°)			
	A	B	C
P1/100	50,4	37,6	16,1
P3/100	17	16,4	2,7

Range of push angle (°)			
	A	B	C
P1/100	129,6	142,4	163,9
P3/100	163	163,6	177,3

Analysis of the point of contact and release of the propulsive phase of the stroke cycle indicated several differences between the sprinters (Table 5). TDC negative value indicated grasping after TDC and BDC negative value indicated releasing after BDC. When speed decreased, the point of contact got close to the top or bottom of the pushrim.

TABLE 5. Top Dead Center (TDC) = 0 cm and Below Dead Center (BDC) = 0 cm on the performances.

		TDC	BDC
A	P1/100	-20,9	-13,9
	P3/100	-8,8	-2,5
B	P1/100	-15,2	-9,9
	P3/100	-6,7	-4
C	P1/100	-4,9	-4,8
	P3/100	1	-0,1

8 DISCUSSION

The purpose of the present study was to examine kinematic differences between elite wheelchair racers (T54) in sprint start. The relationships between selected kinematic factors were analyzed to investigate whether there were significant differences between athletes. However, due to very few subjects one cannot assume the conclusions to be absolutely valid and differences were hard to analyze. This research paper could be considered as a descriptive case study of kinematic variables and their differences between top wheelchair racers. Seating or positioning could be slightly improved through coaching based on the results of this study.

The main findings of the study were as follows:

1. The racer with more velocity had smaller time on propulsive phase. The point where hands contacted the pushrim seemed to get closer to TDC when speed increased.
2. The racer with more velocity had larger movement of body forward in relation to the axle of the wheel at start.
3. The racer with more velocity had larger velocity of wrist in the end of the recovery phase and has larger velocity of elbow in the beginning of the propulsive phase.

According to my knowledge there are only few studies investigating the kinematic variables in wheelchair racing propulsion (Chow et al. 2001; Higgs 1986; O'Connor et al. 1998; Ridgway et al. 1988; Wang et al. 1995). Furthermore, there are found only two published articles about the sprint start of wheelchair racing. Moss et al. (2005) analyzed the first six pushes of a sprint start in over-ground racing wheelchair propulsion with one international male wheelchair athlete. The arm strength and impulse generation of initiation of wheelchair were studied by Tupling et al. (1986).

Comparing literature data on wheelchair racing and on wheelchair sports in general, findings should be dealt with caution due to several reasons. The development of rehabilitation, the results of academic studies and the developments of the equipment are just a couple of reasons to be mentioned. The differences between earlier studies and

the studies of this century can be attributed largely to differences in the wheelchair itself/wheelchair user interface, specifically to the preference of smaller diameter pushrims. This has occurred through developments in racing wheelchair design and the differences in propulsion technique. Very few studies have categorized the pushes from each other. There are also a lot of different definitions of the same variable and experimental set-ups in the studies presented in literature. A considerable amount of studies have simulated racing wheelchair propulsion in laboratory environments using motor-driven treadmills, wheelchair ergometers or simulators. Able-bodied athletes are also used in the studies of the disabled sport, which could give slightly invalid data.

8.1 Wheelchair racing propulsion at start

To initiate movement of the wheelchair/wheelchair user system first the inertia of that system must be overcome. This is a function of starting technique, upper extremity strength and stabilizing potential of the trunk musculature. (Moss et al. 2005; Tupling et al. 1986.) The pushrim is grasped or punched forward and downward, thus rotating the driving wheels. To achieve an explosive sprint start, it depends upon the net force exerted backwards on the ground by the wheelchair/wheelchair user system and on time interval over which these forces are applied. The initial position of the chair, the intent of the movement, the starting technique and the strength of functional muscles in the upper extremities and trunk influence the magnitude and direction of the impulse which is generated. (Tupling et al. 1986.) In order to maintain or increase the acceleration of the wheelchair a larger force must be applied to the pushrim with each subsequent push. However, athlete has less time to apply this force due to increasing velocity of the wheel. Moss et al. (2005) noticed that when velocity increased, the athlete increased the range over which the hand was in contact with the pushrim. At same time, the athlete was contacting the pushrim closer to TDC and releasing the pushrim closer to BDC with each push. (Moss et al 2005.) This was also obtained in the present study (Table 4 and 5). The RPA values were somewhat the same than Wang et al. (1995) have measured (Table 4). With these changes, athletes try to optimize the upper arm, shoulder and elbow to an advantageous position in order to favour the acceleration of the pushrim during the propulsion (Wang et al. 1995). Few studies have also examined the directions of forces applied to the pushrim (Goosey –Tolfrey et al 2001; Roevald et al. 1994; Veeger et al. 1991). Goosey-Tolfrey et al. (2001) noticed that the ratios of

forces remained relatively constant due to forces were increased proportionally in both tangential and medio-lateral directions. The increase of force was accompanied by an increase in the cycle frequency.

The first push is unique because it starts stationary. The trunk appears to fall forward and the trunk angle decreases (Fig. 17a). In the study by Moss et al. (2005) the elbow appeared to flex slightly at first and then extended rapidly reaching the peak extension at the point of release before returning to a flexed position at start. Where the trunk began to flex with the elbow extended, it allowed the hands to follow further round the pushrim and thus adding to the propulsive effect of the arms. (Moss et al. 2005.) The shoulder angle (Fig. 19) showed that in the beginning of the propulsion the angle decreased when humerus approached the body being almost in a vertical position. The angle increased significantly before releasing. The range of motion might be related to the positioning of the upper arm in a favourable position to maximize upper-extremity muscle capacity and efficient propulsion technique. The differences between Moss et al. (2005) and the present study can be attributed largely to differences in the definitions of the shoulder angle.

The second push and thus the subsequent pushes are different from the first push since those pushes are the first pushes when the racer has to contact the pushrim while the wheelchair and thus the wheelchair wheel are in motion. The movement of the trunk also decreased during the propulsion (Fig. 17b). As the wheelchair racing speed was increased, the variations of the trunk angle decreased (i.e., the athlete's upper trunk became more horizontal). The same body positioning was also observed by Wang et al. 1995 and O'Connor et al. 1998. The third push and the subsequent pushes seemed to follow the second push, but the range of motion of the trunk is reduced. This was largely due to the reduced flexion at contact. (Moss et al. 2005.)

The trunk angular velocities were somewhat the same than Moss et al. (2005) have studied. According to Moss et al. (2005) the relative consistency of the trunk angular velocities suggests that the contribution of the trunk to propulsion mechanics is to place the shoulder in favourable position at the start of each push.

Coutts (1990) and Moss et al. (2005) found similar mean peak velocity data for the first push than in this present study. But it should be noted that there were quite different values for the first push between the athletes on the present study. On the third push the velocities were a bit higher than in the other studies (Fig. 13).

8.2 An efficient propulsion at start

The results from the kinematic variables analyzed prior to and on hand contact with the pushrim are significant in developing a more efficient racing wheelchair propulsion technique. The velocity of the wrist on hand contact with the pushrim and the technique of transferring that velocity to the pushrim are major factors that determine the velocity of the wheelchair. (O'Connor et al. 1998.)

The results showed that that the mean duration of the propulsive phase decreased with all athletes while the recovery phase increased on subject A and C and decreased on subject B. During the third cycle in the Max trial the cycle time was fastest on the subject B, which furthermore explained that this subject used less time on 10 meter than other subjects. Moss et al. (2005) found similar mean percentages of the propulsive phase and the recovery phase than showed in this present study (Table 3). Also the mean push and recovery times were almost identical with their study. Less time on the pushrim minimized the risk for a decelerating force to be applied to the pushrim. However, decreased time on the pushrim also indicates that there would be less time to apply force to the pushrim. (Moss et al. 2005.) It could be evaluated that the push time is more crucial than the recovery time in the start. Other researchers have found different values for these variables but none of them reported the results of the start.

Wang et al. (1995) have come to the conclusions that to maximize wheelchair racing speed, it is critical to obtain the maximal shoulder and elbow velocities at initial contact of the propulsion phase and the maximal wrist velocity in the end of the recovery phase. The elbow velocity plays a greater role in preloading the chest, which facilitates involvement of more muscle mass in the propulsion phase. The present study showed some of these statements to be true. The racer with more velocity had larger velocity of wrist in the end of the recovery phase (just before the hand contact) and had larger velocity of elbow in the beginning of the propulsive phase (just after the hand contact)

(Fig. 14, Fig. 15 and Fig. 16). Although Moss et al. (2005) noted that their velocity profile did not indicate a braking effect caused by the hand travelling at lower velocity compared to the pushrim at the instant of contact. According to them this is due to the subjects ability to match the speed of the wheel at relatively slow speed of the first pushes of the start. O'Connor et al. (1998) found a little bit higher values for the elbow velocities in the end of the recovery phase (O'Connors' preparatory phase) comparing to this study.

Positioning and the size of the pushrim are also factors determining the efficient propulsion. The degree of trunk mobility and control may be a limiting factor in the leg-positioning options of the athlete. Any conclusions of a better start positioning, according to this present study, cannot be drawn due to the small number of subjects. Aerodynamic positioning has become a major component in optimising wheelchair racing performance. It should be reminded that each sprint start was performed from a stationary start along a 10 meter portion of an indoor running track, so it could be assumed that there was minimal air resistance. Van der Woude et al. (1988) showed that smaller pushrims are more efficient than larger pushrims when measuring the physiological parameters. Increasing pushrim diameter had a significant effect on movement pattern of the upper arm in the sagittal as well the frontal plane of motion. On the other hand, the pushrim cannot be too small (Morrow et al. 2003). In this present study all pushrims were somewhat the same size and thus did not give any advantages to any of the subjects.

8.3 Kinematic differences between the wheelchair racers

No significant differences in kinematic variables were found between the athletes due to small number of subjects. However, subject A had the fastest cycle time on the first cycle at start. It could be assumed that this was due to the fastest wrist velocity in the end of the first recovery phase and also the fastest elbow velocity in the beginning of the second propulsive phase. The mean elbow velocity during the first push was highest. In addition, subject A had more trunk motion at start than other subjects. The combination of these factors might be the cause for the fastest cycle time. Subject B had the fastest third cycle. The results showed that the wrist velocity in the end of the second recovery phase and the elbow velocity in the beginning of the fourth propulsive

phase were higher than other subjects had. Changes in shoulder angle were also the largest in the third cycle. This could be due to preloading the muscles of upper arm, which facilitates involvement of more muscle mass in the propulsion phase. The changes in shoulder angle could put the arm in an optimal position to apply more force to the pushrim. However, further studies should be conducted in this area to confirm these observations.

8.4 Recommendations for future studies

It should be emphasised that the muscles at work and therefore EMG of the upper extremities and trunk muscles must be included in the future studies. The maximum propulsion impulse which can be developed by an athlete depends also on the athletes particular starting technique, and upon the strength of functional upper extremities and trunk. The limiting factor for racing wheelchair propulsion velocity could be the force-velocity relationship of the muscles involved in propulsion.

In addition, the magnitude and direction of the forces must be examined. Studies concerning optimal starts should also analyze the wrist trajectory angle which is the angle at which the wrist approaches the pushrim. This angle contributes to the velocity or force generated tangentially (force acting around the hub causing rotation) or radially (force directed toward the hub of the wheel). This was studied by Goosey-Tolfrey et al. (2001), O'Connor et al. (1998) and Roevald et al (1994). A sufficient amount of radial force is needed to help maintain friction between the hand and the pushrim; otherwise the hand might slip off the pushrim (O'Connor et al. 1998). Several materials i.e. friction tape, sap and suede gloves are used to improve the quality of the contact. It goes without saying that this is crucial for the optimal start.

Future studies should concentrate on three-dimensional analysis due to the fact that the method will give more accurate information, for example about the movements of the elbow. Even though Goosey and Campbell (1998) analyzed the bilateral symmetry of the elbow movement pattern during wheelchair propulsion and it was valid for their group, this did not appear to be the case for the subjects observed in this study and was not analyzed.

This study used cinematography to identify the instants of contact and release of the pushrim. The accuracy of the cinematographic method being used to identify the wheelchair propulsion phases may have been questionable, since there were several frames which were rather difficult to assign to either the propulsion or the recovery phase. Due also to speed of hand movement and insufficient image clarity, the identification of the propulsion and the recovery phase was extremely difficult but it was made as accurate as possible. Despite of this inaccuracy, this method has been widely used in wheelchair propulsion literature. Analysis of the velocity profile and using the temporal information of the video film revealed features in the velocity profile that appeared to be consistent with propulsion and the recovery phase thus confirming the data.

Evaluating the biomechanics of wheelchair propulsion has been limited by the available instrumentation and the apparent lack of coordination between the investigators. In the future, it is crucial to use a standardised method and definitions for dividing the propulsion to phases. Wang et al. (1995) investigated three-dimensional kinematic features of the wheelchair across four selected speeds. They used a timing device for dividing the propulsive and the recovery phase of a cycle during wheelchair propulsion. This timing device consisted of a light emitting diode (LED) box. Wang and Beale (1996) made a technical note of this same method and noticed that the propulsion phase was approximately 10 % in comparison with the results of the method using cinematography. However, the differences may also be due to some other factors, such as chair style, seating positions, power output demands, training experiences and the modification of the wheelchair propulsion techniques. Variations in the degree of the spinal cord lesion (complete vs. incomplete) have a significant impact on the biomechanical variables, which further confounds the results. (Wang & Beale 1996.)

However, this study showed the significance of analyzing the start technique of wheelchair racer and the importance of using a natural environment and the athletes wheelchair. But there are several possible sources for errors in kinematical measurements obtained in this study. In addition to the possible errors due to manual digitizing, limited resolution of the video images and the use of nonsynchronized cameras define this study as a descriptive study.

In conclusion, it was found that in order to adapt a more efficient start technique, an athlete must (a) perform the propulsion phase faster and faster as the racing speed increases; (b) maximize the velocity of the wrist in the end of the recovery phase and the velocity of the elbow in the beginning of the propulsive phase; (c) use more trunk forward lean to develop a greater vertical motion and assisted acceleration. Caution should be taken when generalising the specific values presented to the wider wheelchair racing athletes. However, the findings are worthy for further investigation and could be used through coaching.

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APPENDIX

Appendix 1: Information for the participant and agreement



APPENDIX

Appendix 1: Information for the participant and agreement

The Kinematic Differences between Racing Wheelchair Propulsion in 100 m (T54) in start

INFORMATION FOR THE PARTICIPANT AND AGREEMENT

It is required in researches which are done with people, to let each participant know the risks and benefits of the research. Prior to the experiment, each participant has to be voluntarily involved in that experiment.

Athletes' Personal and Wheelchair Data:

Name: _____

Gender: _____

Date of Birth: _____

Weight: _____ kg Height: _____ cm

Disability: _____

Level of Spinal Cord Damage: _____

Years in Wheelchair: _____

Wheelchair Model: _____

Diameter of Pushrim: _____

Diameter of Wheel: _____

Achievements: _____

Years of Racing: _____

Practises per week (hours/week): _____

Use of Gloves when Racing: _____

Other: _____

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1. The contact information

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2. The background information

The experiment is done in co-operation with KIHU-Research Institute for Olympic Sports, Department of Biology of Physical Activity (University of Jyväskylä), Kuortane Training Center and Finnish Paralympic Committee.

3. The goal and purpose of the experiment

The experiment focuses on racing wheelchair propulsion in sprint start. The goal is to find differences in the kinematic features and therefore try to find an optimal start for wheelchair racing. Researchers also film wheelchair propulsion so that the athlete can have a interactive feedback from his own performance. The analysis of the mechanical features of wheelchair propulsion will provide useful information to enhance the development of propulsion and with the same time improve the athletes performance.

4. Methods

This pilot research studies wheelchair propulsion by biomechanical methods. Each participant will take few maximum wheelchair racing starts, few start on 80 % and the rest start on 60 %. Between the starts there are few minutes to recover.

The kinematic data will be collected using two high-speed cameras in line. There are acceleration sensor fastened to the wheelchair. Radar measures the speed of the wheelchair. Reflective markers will be placed on ten anatomical positions of the participant's or wheelchair's other side: wheelchair hub and push rim, back of the ear, top of the head, shoulder (lig. A-C), elbow (epicondylus lateralis), wrist (processus styloideus ulnae), hand (third metacarpal), hip (spina iliaca anterior superior) and knee (patella's proximal point).

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5. The risks and disadvantages

There are minor risks and disadvantages in this experiment. It can be a little physically stressing but no more than normal racing wheelchair practises. The risk can be some kind of minor locomotor injury. There is no physician at the place but the physician can be contacted immediately by phone.

6. How the results are used

The experiment is done in co-operation with KIHU-Research Institute for Olympic Sports, Department of Biology of Physical Activity (University of Jyväskylä), Kuortane Training Center and Finnish Paralympic Committee. The researcher will use the data to make a master thesis of this experiment. Also the summary of results is done for each participant and their coaches. In addition the results might be used in the national and international research articles.

7. Participant's Rights

All the results are dealt with confidentiality and the names won't be published. If you have any questions about this experiment feel free to ask researchers about the methods, risks, advantages etc. Participation in this experiment is entirely voluntary and participants can interrupt the experiment when ever he/she feels like it.

8. Agreement

I have read this paper and understood the purpose of this experiment. I also have understood that there are minor risks. I will be a volunteer in this experiment. I have rights to interrupt this test when ever I want. I also give the full rights for the researchers to use my results in their work.

I am healthy and have no locomotor disease or injury, and I have not had fever in the past two weeks. The researcher and I have a copy of this agreement.

Kuortane 23.6.2004 _____

Participant

Kuortane 23.6.2004 _____

Researcher