Biomechanics in Paralympics: Implications for performance

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Biomechanics in Paralympics: Implications for performance

Brief review

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Abstract

Purpose: To provide an overview of biomechanical studies in Paralympic research and their relevance for performance in Paralympic sports. Methods: Search terms ‘Paralympic Biomechanics’, ‘Paralympic Sport Performance’, ‘Paralympic Athlete Performance’, and ‘Paralympic Athlete’ were entered into the electronic database PubMed. Results: Thirty-four studies were included. Biomechanical studies in Paralympics mainly contributed to performance enhancement by technical optimization (n=32) and/or injury prevention (n=6). Also, biomechanics was found to be important in understanding activity limitation caused by various impairments, relevant for evidence-based classification in Paralympic sports (n=6). Distinctions were made between biomechanical studies in sitting (41%), standing (38%), and swimming athletes (21%). In sitting athletes, kinematics and kinetics in wheelchair propulsion were mostly studied, mainly in spinal cord injured athletes. Also kinetics and/or kinematics in wheelchair basketball, seated discus throwing, stationary shot putting, handcycling, sit-skiiing and ice sledge hockey received attention. In standing sports, kinematics of amputee athletes performing jump sports and running, and the optimization of prosthetic devices were primarily investigated. No studies were reported on other standing sports. In swimming, kick rate and resistance training were mainly studied. Conclusions: Biomechanical research is important for performance by gaining insight into technical optimization, injury prevention and evidence-based classification in Paralympic sports. Future studies are advised to also include physiological as well as biomechanical measures, allowing the assessment of the capability of the human body as well as the resulting movement.

Keywords: Physical disability, adapted sports, sports performance, performance enhancement, athletes.

Introduction

At the 2012 Paralympics, one of the world’s largest sporting events, over 160 countries and more than 4000 athletes with different disabilities competed in over 500 medal events (www.paralympic.org). Twenty-eight sports were included: Twenty-three summer sports (Archery, Athletics, Boccia, Canoe, Cycling, Equestrian, Football 5-a-side, Football 7-a-side, Goalball, Judo, Powerlifting, Rowing, Sailing, Shooting, Sitting volleyball, Swimming, Table tennis, Triathlon, Wheelchair basketball, Wheelchair dance, Wheelchair rugby and Wheelchair tennis) and five winter sports (Alpine skiing/ snowboarding, Biathlon, Cross-country skiing, Ice sledge hockey, Wheelchair curling).

Biomechanical analyses have proven to be extremely important in enhancing sports performance. For Paralympic athletes, biomechanical analysis is even more important, since it will help understand how different impairments limit activity and sports performance. To obtain a better understanding of Paralympic sports and the performance determining factors, it is important to give an overview of biomechanical research and its relevance for performance conducted in Paralympic sports. Relatively recently Keogh published a review on biomechanics in Paralympic summer sports. The present review updates and expands upon the review conducted by Keogh, however is unique in giving an overview of biomechanical research and its relevance for performance in Paralympic sports and Paralympic athletes as it covers all sports and disability groups which have been published in the literature, including
Paralympic Winter sports. Following this overview, we hope to obtain more insights into the relevance and practical applications of biomechanics in Paralympic sports and athletes. Specifically, we hope to distill relevant practical advices for coaches and athletes, ultimately directed at improving Paralympic sports performance.

Methods

With the intention to obtain all papers reporting on biomechanics in Paralympic sports and Paralympic athletes, the key words “Paralympic Biomechanics”, “Paralympic Sport Performance”, “Paralympic Athlete Performance” and “Paralympic Athlete” were entered into PubMed (July 2016). All studies on biomechanics in Paralympic and World Class athletes were included, including case-studies. Interviews, editorials, reviews, studies not available online and studies not in English were excluded (Figure 1).

Results

Twenty articles were identified using the keywords “Paralympic Biomechanics”, 124 using the keywords “Paralympic Sport Performance”, 110 using the keywords “Paralympic Athlete Performance”, and 220 using the keywords “Paralympic Athlete”. After applying the exclusion criteria, eleven, ten, one, and seven articles were selected respectively. Based on the authors’ knowledge, five more studies were included on biomechanics in Paralympic athletes. In total, 34 studies were included (Tables 1-3). One case-study was selected using the keywords “Paralympic Biomechanics” and two using the keywords “Paralympic Sport Performance” (Table 4). Based on the authors’ knowledge, four more case-studies were included (Table 4).

Biomechanical studies in Paralympic athletes (non case-studies) mainly contributed to performance enhancement by technical optimization (n=32) and injury prevention (n=6) (Tables 1-3). Also, biomechanics were important in evidence-based classification in Paralympic sports (n=6; some studies addressed more than one of these points) (Tables 1-3). In the current review, sports were subdivided into three main groups based on Bernardi et al.: sitting, standing, and visually-impaired athletes. However, no studies specifically on visually impaired athletes and biomechanics were found. Instead, several studies on biomechanics and swimming were included, and we defined swimming as a third group, replacing the group of visually-impaired athletes.

Studies on biomechanics in Paralympic summer (n=29, 85% of the included studies) and winter sports (n=5, 15% of the included studies), the number of participants, type of sport, type of impairment, test used, and main outcome are presented (Tables 1-3). Thirteen studies (38% of the included studies) were performed during the Paralympic Games or World Championships, whereas the remaining twenty-one studies (62% of the included studies) were performed in a laboratory setting studying Paralympic athletes. Furthermore, 41% (n=14) of the studies were performed on sitting sports, 38% on standing sports (n=13), and 21% (n=7) on swimming. Sports were analyzed from a kinematic and/or kinetic point of view. In sitting athletes (n=14, 41% of the included studies), summer sports (n=9, Table 1) were represented more than winter sports (n=5, Table 1).

Sitting sports

Regarding summer sports, kinetics and kinematics of wheelchair propulsion were widely studied (n=4) in terms of push-rim forces, wrist biomechanics, and shoulder and elbow motion. Forces, moments, and kinematics were described during tests in which subjects propelled a standard daily wheelchair, equipped with a SMARTWheel® on a computer controlled dynamometer at different speeds. These studies were performed in order to understand and prevent upper limb injuries such as wrist, shoulder and elbow injuries in manual wheelchair users; they all contributed to the creation of a reference database on daily wheelchair propulsion technique in elite athletes, which eventually could be used to enhance performance and prevent injuries in sports.

Biomechanical research also generated evidence relevant for optimizing performance and evidence-based classification in several summer sports (wheelchair basketball, handcycling, discus throwing, and stationary shot putting). Wang et al. investigated the kinematics and kinetics of wheelchair basketball. Coaches are advised to focus on increasing sitting height and range-of-motion of shoulder internal rotation and elbow flexion, elbow extension and range-of-motion of wrist extension, and quick visual reaction time to increase the average rebounds, points and number blocks per game respectively. Range-of-motion and muscle strength of wrist flexion/extension should receive more attention in wheelchair basketball training. Hence applying wrist-shoulder- and arm skills training should enhance wheelchair performance.

Handcycling could successfully be modeled using the power balance model (Table 1), providing insights into the power production and losses during handcycling. The power balance allows predictions of performance in cyclic activities. For hand cycling, power output of the handcyclist, average power loss to air friction, internal friction and rolling friction, and average change of mechanical energy of the system (hand cyclist and handcycle together) are taken into account. In turn, the power balance model can be used for estimating exercise responses of Paralympic athletes when there is no possibility for direct measurements.

In seated discus throwing, whole body position and feet position characteristics provided key information on the relationship between throwing technique and the throwing frame (customized sport equipment attached onto the plate from where the discus is thrown) (Table 1). The base of support of elite discus throwers in F30 classes (athletes having moderate to severe hypertonia, ataxia and/or athetosis in limbs and/or trunk, varying from severe to moderate loss of functional control over the classes F31 to F34 respectively www.paralympic.org) could be described by the feet position as well as the whole body position. This knowledge contributes toward optimizing the competitive conditions for seated discus throwers, such as the design of the throwing frame for seated discus throwers, the interaction between the throwing technique and the throwing frame, and the throwing technique. Also, this knowledge is relevant for the debate on the design of throwing frames and classification in seated discus throwing. Kinematic analysis has increased the understanding of stationary shot putting (Table 1). To develop an evidence-based classification system for stationary shot putters, performances of 114 Paralympic athletes were analyzed (Table 1). The methods of analysis (comparative matrices, performance continuum, and dispersion plots) were found to work well in obtaining biomechanical variables and helped to better understand the dispersion of classification-related variables. The results from stationary shot putting and seated discus throwing provide important information to enhance performance, and contribute to further development of evidence-based classification, which will ensure fair and equal competition in these sports. Coaches and athletes should focus on increased velocity and angle of the shot at release.

For winter sports, only cross-country sit-skiing and ice sledge hockey have been studied. Kinematics in cross-country sit-skiing showed that speed, and therefore performance, decreased during the race (substantiated by evaluating changes in the kinematic
parameters cycle speed, cycle duration, push phase speed, recovery phase speed, pole inclination, trunk inclination and shoulder-hand distance) (Table 1). As this speed decrement was attributed to early fatigue and a relatively low physical fitness, slower cross-country sit-skiers were advised to increase their physical fitness by focusing on strength and explosive power training and by improving maximal aerobic power and glycolytic capacity, to optimize their performance. The biomechanics of the double poling technique in cross-country sit-skiers were successfully analyzed using unique field data obtained via markerless kinematic analysis in Paralympics competition. Coaches and athletes are advised to focus on improving physical fitness and use the markerless kinematic analysis technique based on video-analysis during competition to visualize and analyze the double-poling techniques to improve performance in cross-country sit-skiing.

The interaction between the athlete and the equipment used in sit-skiing was addressed by designing a new sit-ski to facilitate control of the center of mass (CoM) and inertia of the sit ski/skier system, in the anterior-posterior direction (Table 1). Control of the CoM in the anterior-posterior direction influences sit-ski dynamics and how the ski mechanically interacts with the snow surface, which was relevant for enhancing performance. In ice sledge hockey, high correlations were found between upper-body strength, power and sprint performance in highly trained athletes. The ability to produce high frequency propulsion (i.e. a poling push-off in the opposite direction of movement) was found to be important for sprint abilities (Table 1). In addition, heavy upper-body strength training (6-weeks, 3-weekly sessions of 3x6-8RM) improved upper-body strength as well as sprint abilities (Table 1). Strength gains correlated with improvements in sprint abilities. In particular, a high load during strength training was effective for enhancing sprint abilities (especially acceleration) in sports where upper-body acceleration and maximal speed are important for performance.

**Standing sports**

In standing sports (n=13), research focused mainly on unilateral lower limb amputees (n=9, Table 2) compared to bilateral lower limb amputees (n=3, Table 2). Athletes with a transtibial amputation (TTA, n=9) were most researched compared to athletes with a transfemoral amputation (TFA, n=3). Only one study evaluated biomechanics in standing athletes with cerebral palsy (CP), and one study with visually-impaired standing athletes.

Regarding summer sports in standing athletes, research increased the understanding of activity limitation and performance determining factors in Paralympic athletes. Several studies (n=4, Table 2) analyzed the kinematics of unilateral amputee long and high jumpers. In able-bodied (AB) athletes, a long-jump model has been established, where a positive relation exists between approach speed and distance jumped. Optimal take-off technique included lowering the CoM during the last few steps, obtaining the right body posture at touch-down, and successfully ‘pivoting’ over the take-off leg to generate sufficient vertical velocity while minimizing losses in horizontal velocity. Female TTA conformed to the long-jump model established for AB long-jump technique, although some technical adaptations were noticed. These adaptations caused a less effective use of the horizontal approach speed in these athletes compared to AB and male amputee athletes. In contrast, TFA did not conform to the long-jump model, possibly because of the excessive lowering of their CoM at touch-down, creating a greater downward vertical velocity which negatively influenced jump
performance (Table 2).\(^8\) Coaches and athletes should be cautious about translating techniques used by AB long-jumpers to athletes jumping with prostheses. In addition, while differences in technique were observed (Table 2) depending on take-off strategy,\(^27\) take-off using the prosthetic limb versus take-off using the intact limb did not affect jump distance. However, a low number of athletes were included in the study, so conclusions must be interpreted with caution.\(^27\) Lastly, although a longer residual shank (stump length) may provide a longer and stronger lever arm, Nolan et al.\(^10\) found that residual shank length was not an important determinant of long-jump performance, suggesting it is appropriate for all TTA long-jumpers to compete in the same class. In the high jump, TTA athletes showed some similarities in jump technique compared to AB athletes (Table 2).\(^9\) Even though an understanding of the differences in technique compared to AB athletes has provided significant information for coaching, and has the potential to contribute to performance enhancement in lower limb amputee long-jump and high-jump athletes, a better understanding of the mechanisms of amputee jumpers is still needed.\(^9\) As residual shank length had no effect on distance jumped, technique, prosthesis and training play a more important role in long-jump performance\(^10\) and are advised to be addressed in jump sports training sessions. In addition, these findings are important for evidence-based classification, to establish fair and equal competition in Paralympic jumping athletes.

Amputee running has received considerable attention\(^2,4,13,31,35\) (Table 2). Lowering the prosthetic knee joint center in unilateral TFA runners improved inter-limb symmetry, and subsequently running velocity,\(^13\) whereas running on standard running prosthesis resulted in a larger inter-limb asymmetry (Table 2).\(^4\) These findings suggest that by improving the method of alignment of the prosthesis running performance can be increased.\(^13\) In addition, three studies\(^2,31,35\) evaluated unilateral as well as bilateral TTA sprinters (Table 2). Arellano et al.\(^2\) performed a study on mediolateral foot placement variability and found that maintaining lateral balance became increasingly difficult at faster speeds but was equally challenging for sprinters with and without a unilateral TTA.\(^2\) For bilateral TTA athletes, it was most challenging to maintain lateral balance. In addition, asymmetries in medio-lateral foot placement were seen in unilateral TTA sprinters, suggesting that the use of running-specific prostheses results in a compensatory foot placement strategy for maintaining lateral balance in sprinters with unilateral TTA.\(^2\) Furthermore, leg stiffness was important in sprinting (Table 2) (increased vertical stiffness is associated with faster speed and decreased contact time, while decreased leg stiffness in affected legs with running specific prostheses was due to lower peak ground reaction forces and increased leg compression with increasing speeds) and was different between biological legs and affected legs with running specific prostheses.\(^35\) Also, a low step count (<50 steps) was found to be a factor for success in lower-limb amputee sprinters since the converse may indicate the prosthesis requires further adjustments.\(^31\) Although Habora\(^10\) showed that amputation side does not influence sprinting performance, a more recent study on maximum speed curve running in TTA athletes showed slower speed in the curves with the affected leg on the inside compared with curves with the affected leg on the outside.\(^12\) Orientation of the affected leg seemed to limit speed more than curve-running direction.\(^12\) These insights help to understand the race-based behavior of amputee athletes and provide information for the discussion on the performance of lower-limb prostheses.

However, actual ‘in competition analysis’ similar to that of AB sprinters\(^45\) has yet to be undertaken for Paralympic sprinters.

The only study on standing athletes with CP, and the only study involving EMG, claimed that power output during a 30-sec Wingate cycle test was higher in AB (AB) athletes compared to athletes with CP, whereas both groups were equally fatigued (Table 2).\(^20\) Bilateral EMG activity of five muscles (erector spinae, gluteus medius, biceps femoris, gastrocnemius, vastus lateralis) was measured in both legs during a 10-sec sprint test, a 30-sec
Wingate anaerobic sprint test and in a rested state. No differences in mean muscle activity were found between the able-bodied and CP groups. For all measured muscles but the vastus lateralis, EMG amplitude decreased significantly over the trial in both limbs in CP and able-bodied groups. Vastus lateralis activity remained unchanged. Elite athletes with CP seem to have the ability to adapt towards levels of AB athletes, which can most likely be attributed to their high-level of training over many years.\textsuperscript{20}

In a group of visually-impaired athletes, athlete guides (those who assist visually-impaired running athletes) and athletes with upper- and distal lower limb deficiencies, isokinetic muscle strength and self-reported musculoskeletal complaints were investigated.\textsuperscript{29} Increases in knee flexor and extensor muscles in both lower limbs were found over time (assessments took place at three time points over one year working towards a competition) (Table 2).\textsuperscript{29} In addition, muscle imbalance was associated with the occurrence of knee and thigh complaints. The simultaneous investigation of athletes’ musculoskeletal complaints and muscle strength may contribute to the identification and treatment of injuries in Paralympic athletes by obtaining better understanding into satisfactory musculoskeletal development.\textsuperscript{29}

Insert Table 2 about here

Swimming

Seven studies analyzed swimming athletes (Table 3).\textsuperscript{11,14-16,18,26,33} A 6-week dry-land resistance training program improved swimming performance by eliciting increased strength and power, dive starts, and free swimming velocity (Table 3).\textsuperscript{14} Also, strengthening the shoulder girdle increased muscular and joint stability and control, reducing the risk of injuries. The evaluation of biomechanics in relation to training thus seems important, as adequate training improves technique and consequently reduces the risk of the occurrence of injuries. To enhance swimming performance and reduce the risk of injuries, coaches and swimmers are encouraged to undertake continuous dry-land training programs throughout the season.\textsuperscript{14} From an anthropometric point of view, especially male Paralympic swimmers with low-severity physical disabilities and female Paralympic swimmers with mid-severity physical disabilities, swimmers should be encouraged to develop muscle mass and upper body power to enhance performance (Table 3).\textsuperscript{16} To further optimize swimming performance, coaches can benefit from identifying four specific measures in swimming - time, distance, velocity and force - during the three primary phases of the swim-start: the block, flight, and underwater phases. During swim-starts, the free-swim period is a critical phase for all Paralympic swimmers regardless of the severity of their disability, while the block and underwater phase are specifically critical for upper body, lower body, and palsy disabilities (Table 3).\textsuperscript{15} This is because large correlations were found between free-swim velocity and the International Point Score (IPS, a performance level), and the free-swimming velocity accounted for between 67\%-75\% of the variation in 50-m performance. Also, a lower velocity during the block and underwater phases was associated with slower times towards 15 m in all disability groups (i.e. upper body, lower body, palsy).\textsuperscript{15}

An increased kick rate contributed to faster swimming speeds (Table 3).\textsuperscript{18} The kick rate and amplitude profile that Paralympic swimmers showed in Fulton et al.\textsuperscript{33} (i.e. a large amplitude kicking and a decreased kick rate) are appropriate for optimizing net force (Table 3), relevant information for developing training programs.

Biomechanics-based classification in swimming was also investigated by relating passive drag force to swimming class. Negative associations between drag force and swimming class were found, where the most severely impaired swimmers experienced highest
However, as the mean difference in drag between classes was found to be inconsistent, it was concluded that the current classification system does not always differentiate clearly between swimming groups.\textsuperscript{11} Insert Table 3 about here

**Case-studies**

Case-studies on wheeling,\textsuperscript{38} cycling,\textsuperscript{37} long-jump,\textsuperscript{36} and sprinting\textsuperscript{39-42} Paralympic athletes are listed (Table 4). These case-studies have helped athletes to choose an optimum hand rim diameter for wheeling.\textsuperscript{38} In addition, they helped to optimize equipment-user interface (Table 4),\textsuperscript{37} both important for improving sports performance. The case-study of an upper limb amputee long-jumper showed that the addition of extra arm mass did not improve jump performance (Table 4).\textsuperscript{36} Amputee sprinting has received most attention (n=4). Specifically, there has been much debate in the literature\textsuperscript{39,40} regarding the biomechanics of amputee sprinting compared to AB sprinting, with a focus on whether amputee sprinters have an advantage when competing against AB sprinters, thus offering a unique take on classification.

It is established that increased hip work on the prosthetic limb acts as the major compensatory mechanism that allows TTA athletes to run. Considering the biomechanical adaptations of TTA sprinting athletes using dedicated prostheses, additional compensatory mechanism have been identified (i.e. increased extension moment and increased amount of work done at the residual knee) (Table 4).\textsuperscript{42} Comparing (prosthetic) limb kinematics of amputee sprinters to AB sprinters, TTA sprinters were similar to AB sprinters whereas TFA sprinters showed larger kinematic asymmetry between contralateral limbs during sprinting and showed a gait more typical of walking.\textsuperscript{41} Additionally, comparing a bilateral TTA sprinter to AB sprinters, physiologically they were similar (Table 4),\textsuperscript{39} while clear biomechanical differences were demonstrated.\textsuperscript{39,40} The TTA sprinter demonstrated a shorter swing time (possibly due to the reduced mass of the prostheses compared to a biological limb) and an increased contact time. The ground reaction force seen have been cited as a determinant of increased sprinting speed.\textsuperscript{46} However, the reduced ground reaction force seen for this TTA sprinter was markedly reduced compared to the AB sprinters, suggesting force impairment\textsuperscript{39,40,47} which may be compensated by the increased contact time to produce a similar propulsive impulse. Insert Table 4 about here

**Discussion**

The aim of this review was to give an overview of biomechanical research and its relevance for performance in Paralympic sports covering all sports and disabilities which have been published in the literature. Several practical matters regarding technical optimizations, injury prevention and classification were found to help coaches and athletes to improve.

Besides providing understanding in technical optimization and injury prevention, biomechanical research is fundamental for evidence-based classification, where it is important to understand how different impairments limit sports activities.\textsuperscript{48} To be able to classify athletes in such a way that the influence of the athletes’ impairment on sport performance is limited, biomechanics have been studied in sitting\textsuperscript{5,6,17,32} and swimming athletes,\textsuperscript{11} while limited data\textsuperscript{10} have been reported on standing athletes. Future research is encouraged to study
biomechanics in the context of evidence-based classification, to ensure fair and equal
competition and optimal performance in Paralympic athletes.

Paralympic summer sports (n=29, 85%) were studied far more than winter sports (n=5,
15%) in sitting as well as standing athletes. Obviously, the number of summer sports (n=23)
performed at the Paralympic Games is higher than the number of winter sports (n=5).
However, out of five winter sports, only cross-country sit-skiing and ice-sledge hockey were
evaluated using biomechanical analyses. The results on cross-country sit-skiing and ice-sledge
hockey provided scientific evidence for setting up optimal training programs, directed to
improve performance in elite cross country sitting athletes and ice-sledge hockey players.21,28
Future research is encouraged to investigate biomechanics in alpine skiing, snowboarding,
biatlon, and wheelchair curling, to provide coaches and athletes with scientific evidence
useful for optimizing performance or to establish evidence-based classification in (new)
Paralympic sports. Biomechanical understanding already provides insights in performance
enhancement in several summer sports3-6,8-13,17,18,22,24-27,30,32-34 and is important for developing
training programs aimed at optimizing performance and preventing injuries.

Laboratory testing allows studying movements in a well-structured and controlled
way. However, field based testing has the potential to provide a more valid outcome than
laboratory testing because athletes are in their natural environment.49 It has been stated that
specific knowledge relevant for optimal performance is rooted in a direct experience of a
meaningful individual-environment process, and that the environment is therefore of influence
on the decisions athletes make in competition.50 Consequently, the environment as well as the
ecological validity of the studies (i.e. are the participants in the studies cited in this review
performing sports specific movements or performing as they would in competition?) play an
important role in performance and classification respectively. Future research is encouraged
to continue to link the well-controlled laboratory outcomes to valid field based outcomes.

Wheeled sports and SCI athletes take a prominent place in the literature. Many
biomechanical studies were performed in wheeled sports, mainly because of the complex
athlete-device interface, in which changes in both the athlete and the wheelchair affect
performance.49 Especially after the introduction of the SMARTWheel44, data collection of
forces and moments applied to the push-rim of daily wheelchairs became much easier,
increasing biomechanical data collection in wheelchair research. In addition, SCI is a
devastating paralysis resulting in many secondary impairments, that primarily affects young
adults. Despite a relatively low incidence of SCI (9.2-83 per million people per year), and an
estimated prevalence of 223-755 per million inhabitants,51 this can explain the fact that SCI,
and therefore wheelchair athletes and wheeled sports, is a well-researched area. However,
there is a paucity of research in to other impairments and non-wheeled sports. This suggests
that future biomechanics research will have a lot to offer in developing gains in performance
and injury prevention of Paralympic athletes.

Consistent with a previous literature review on the contribution of biomechanical
research in performance improvement in a selection of summer sports,1 we found that
wheelchair and amputee athletes were studied most frequently, whereas little biomechanical
research has been conducted on visually-impaired athletes or athletes with CP. Yet, as it has
been shown that injuries in visually-impaired athletes are mostly caused by falls,52 usually a
result of instability, it seems that biomechanical research can contribute to gain understanding
in the effect of visual impairment on balance, and subsequently contribute to performance
enhancement and injury prevention in visually-impaired athletes. Future research is
encouraged to investigate biomechanics in a wide range Paralympic sports and extend the
biomechanical knowledge in all fields of sports science.

Besides biomechanical measures, several studies have included physiological
measures,15,20,21,28,39 as the combination of biomechanical and physiological parameters could
teach us even more about performance and performance enhancement, allowing the
assessment of capability of the human body as well as the resulting movement. For example,
comparisons of biomechanical and physiological measures in sprinting athletes showed that
running on dedicated, lower-limb sprinting protheses was physiologically similar but
mechanically different from able-bodied running. Also in cycling, biomechanical
differences were found between able-bodied athletes and athletes with CP, while there were
physiological similarities. Lastly, correlations between physiological and kinematic
parameters were found in ice sledge hockey, indicating that physiological training
adaptations might also affect optimal use of biomechanical principles and technical ability.
Future studies are advised to focus on physiological as well as biomechanical principles to be
able to better understand performance and performance enhancement.

Practical Applications and Conclusions

Biomechanical research has contributed greatly to increased understanding of performance
enhancement and injury prevention in Paralympic athletes. Also, biomechanical research is
fundamental for evidence-based classification, where it is important to understand how
different impairments are limiting sports activity. Research has focused mainly on athletics,
wheeled sports, (hand)cycling, swimming, sit-skiing and ice sledge hockey, largely in SCI
and amputee athletes. No biomechanical research was found on archery, boccia, canoe,
equestrian, football, goalball, judo, power lifting, rowing, sailing, shooting, sitting volleyball,
table tennis, triathlon, alpine skiing and snowboarding, biathlon and wheelchair curling.
Besides continuing to deepen knowledge on athletics, wheeled sports, (hand)cycling,
swimming sit-skiing and ice sledge hockey, future biomechanical research is encouraged to
investigate a wider range of Paralympic sports, to enhance performance, prevent injuries, and
relate research in elite athletes to daily rehabilitation practice. Future studies should include
physiological and biomechanical analysis to better understand performance and performance
enhancement.
References


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<td>6</td>
<td>Table Tennis; weight training; Swimming, Target Shooting, W/chair Racing</td>
<td>SCI, Spina Bifida</td>
<td>WC propelling on a dynamometer at 1.3 m/s and 2.2 m/s to assess 3D pushrim forces, wrist, shoulder, and elbow biomechanics</td>
<td>Pushrim forces: Peak force tangential to pushrim, peak moments radial to hub, maximum rate of rise of tangential force and moment about hub were stable parameters but differed between the two speeds.</td>
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<td>Frossard17[T,E]</td>
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<td>Stationary Shot Putting</td>
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<td>Analysis of 479 attempts by male and female during the 2008 PG</td>
<td>There was a linear relationship between best performance and classification.</td>
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<td>Frossard et al.32[T,E]</td>
<td>Best attempt of the best men (n=4) and women (n=3) at each event.</td>
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<td>Release velocity of shot and angle of shot's trajectory↑ with performance and classification for males and females.</td>
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<td>Frossard et al.5[T,E]</td>
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<td>Seated Discus Throwing</td>
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<td>Video-recording of WBP - 2002 WCh</td>
<td>Multiple combinations of throwing postures - including 3-6 points of contact, throwing from a standing or seated position, using a straddle, stool or chair.</td>
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<td>n participants</td>
<td>Sport</td>
<td>Impairment</td>
<td>Test</td>
<td>Outcome</td>
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<tr>
<td>Frossard et al. 6[T,E]</td>
<td>12</td>
<td>Seated Discus Throwing</td>
<td>F30 class:</td>
<td>Video-recording. Relation between performance and feet positioning - 2002 WCh.</td>
<td>The overall position of the front and back foot had little effect on the performance. Although performance tended to ↑ with distance between the feet in the ML axis.</td>
</tr>
<tr>
<td>Groen et al. 34[T]</td>
<td>4</td>
<td>Hand Cycling</td>
<td>SCI, TFA, PTD</td>
<td>250 m indoor track cycling</td>
<td>PO = 0.20v3 + 2.90v (R2 = 0.95) Mean GE = 17.9% ± 1.6%. Performance can be modeled with a power balance model.</td>
</tr>
<tr>
<td>Wang et al. 22[T,I]</td>
<td>37</td>
<td>Wheelchair Basketball</td>
<td>Multiple</td>
<td>RT, arm goniometry</td>
<td>↑ Elbow and wrist extension ROM = sig ↑ average points.</td>
</tr>
<tr>
<td></td>
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<td>↑ sitting height, shoulder internal rotation and elbow flexion = sig ↑ average rebounds.</td>
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<td>↑ arm length sig ↑ average assists.</td>
</tr>
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<td></td>
<td>Quick vision RT sig ↑ increased number of blocks.</td>
</tr>
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<td></td>
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<td></td>
<td>↑ Wrist Flex/Ext ROM and strength sig ↑ increased overall performance.</td>
</tr>
<tr>
<td>Winter</td>
<td>10</td>
<td>Cross-Country Sit-Skiing</td>
<td>na</td>
<td>Video-recordings during 15 km - 2006 PG</td>
<td>Speed sig ↑ in G1 than in G2 in flat and uphill track. G1 maintained the high-speed better than G2 over the entire race. G1 showed ↑ physical fitness than G2.</td>
</tr>
<tr>
<td>Study</td>
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</tr>
<tr>
<td>Gastaldi et al.</td>
<td>50</td>
<td>Cross-Country Sit-Skiing</td>
<td>Multiple</td>
<td>In competition marker-less kinematic analysis - 2010 PG</td>
<td>Wide variability in gesture due to different disabilities.</td>
</tr>
<tr>
<td>Langelier et al.</td>
<td>-</td>
<td>Sit-Ski</td>
<td>-</td>
<td>Development of a new Sit-Ski design</td>
<td>A four-bar linkage Sit-Ski provided maximal 140 mm of AP CoM adjustment. Increased precision in controlling the AP CoM location improved performance.</td>
</tr>
<tr>
<td>Sandbakk et al.</td>
<td>8</td>
<td>Ice-Sledge Hockey</td>
<td>UL and BL</td>
<td>30 m max sprint on ice. 1RM bench press, pull down and over, front pull before and after 3 weekly sessions of 3x6-8RM strength exercises during a 6 wk intervention</td>
<td>1RM sig ↑ 4-8%. 30 m sprint time sig ↑ 2-3%. Pre- to posttest changes in 30 m sprint time correlated sig with the changes in 1RM for Bench press (r=0.59) and pull down (r=0.60).</td>
</tr>
<tr>
<td>Skovereng et al.</td>
<td>13</td>
<td>Ice-Sledge Hockey</td>
<td>UL and BL</td>
<td>Sprint and strength performance on ice and 1RM strength and peak power in bench press and pull-down</td>
<td>1RM strength and peak power for all exercises sig correlated with total sprint time. No sig relationships between sprint kinematics and 1RM strength and peak power.</td>
</tr>
</tbody>
</table>

AP = Anterior-posterior; BL = Bilateral; CoM = Center of Mass; G1 = Better performing Skiers; G2 = Worse performing Skiers; GE = Gross Efficiency; LA = Leg Amputation; ML = Mediolateral; PG = Paralympic Games; PTD = Post Traumatic Dystrophy; ROM = Range-of-Motion; RT = Reaction Time; SCI = Spinal Cord Injury; UL = Unilateral; Time; WBP = Whole Body Positioning; WC = Wheelchair; WCh = World Championship.
Table 2 Biomechanical studies of standing Paralympic summer sports. The topics technical optimization (T = technical optimization), injury prevention (I = injury prevention) and evidence-based classification (E = Evidence classification) are indicated.

<table>
<thead>
<tr>
<th>Study</th>
<th>n participants</th>
<th>Sport</th>
<th>Impairment</th>
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<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arellano et al. [2][T]</td>
<td>12 AB, 7 TTA</td>
<td>Sprinting</td>
<td>UL and BL TTA, AB</td>
<td>Midline of the body and CoP in the ML direction during running up to maximum speeds on a force measuring treadmill</td>
<td>ML FPV ↑ and was symmetrical across speed in AB and ↑ and was asymmetrical across speed in UL TTA. BL TTA showed the greatest increase in ML FPV with speed.</td>
</tr>
<tr>
<td>Burkett et al. [4][T]</td>
<td>4</td>
<td>Sprinting</td>
<td>UL TFA</td>
<td>Video and force plate analysis during walking and maximal running speed on modified running prosthesis</td>
<td>Lowering the prosthetic knee joint center improved inter-limb symmetry and subsequently running velocity by ± 26%. Better inter-limb asymmetry was identified in walking than in sprinting.</td>
</tr>
<tr>
<td>Dyer et al. [3][T]</td>
<td>7 male</td>
<td>100 m</td>
<td>UL and BL TTA</td>
<td>Video analysis major events from 1996–2012. Step count and step limb-to-limb symmetry characteristics.</td>
<td>A low step count (&lt;50 steps) may help athletes to achieve better results in 100 m sprint. Limb-to-limb imbalances were found.</td>
</tr>
<tr>
<td>Nolan et al. [9][T]</td>
<td>17 female</td>
<td>Long Jump</td>
<td>UL TFA, TTA</td>
<td>Doppler device and video-recordings - 2004 PG</td>
<td>TFA CoM height in the last three steps before TO was ↑ than TTA. From last touch-down to TO, CoM was ↓ in TFA than in TTA.</td>
</tr>
<tr>
<td>Nolan et al. [9][T]</td>
<td>2</td>
<td>High Jump</td>
<td>UL TTA</td>
<td>Video-recordings - 2004 PG</td>
<td>↓ horizontal approach velocity, ↓ vertical TO velocity, ↑ upright position at TD and ↑ hip ROM TO phase compared to AB.</td>
</tr>
<tr>
<td>Nolan et al. [27][T]</td>
<td>10</td>
<td>Long Jump</td>
<td>UL TTA</td>
<td>Doppler device and video-recordings - 2004 PG</td>
<td>At TD before TO prosthetic limb showed significantly ↓ hip ROM and ↓ knee ROM and maximal knee flexion compared to intact limb. Prosthetic limb TO showed more horizontal velocity than intact limb TO.</td>
</tr>
</tbody>
</table>
### Table 2 continued

<table>
<thead>
<tr>
<th>Study</th>
<th>n participants</th>
<th>Sport</th>
<th>Impairment</th>
<th>Test</th>
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</tr>
</thead>
<tbody>
<tr>
<td>McGowan et al. (^{35[T]})</td>
<td>8 (n=2 BL and n=6 UL), 12 AB</td>
<td>TTA (max 7.0-9.7 m/s)</td>
<td>UL and BL TTA, AB</td>
<td>Spring-mass model across a range of speeds wearing specific running prosthesis.</td>
<td>Leg stiffness, remained constant or ↑with speed in intact legs, but ↓with speed in prosthesis.</td>
</tr>
<tr>
<td>Runciman et al. (^{20[T]})</td>
<td>5 CP, 16 AB</td>
<td>Sprinting; T38/T39</td>
<td>CP</td>
<td>PO and fatigue index (%) during a 30 sec Wingate cycle test. Bilateral leg EMG.</td>
<td>PO was sig ↑ in the AB group (10.5 ± 0.5 W/kg) than in the CP group (9.8 ± 0.5 W/kg). Fatigue index was similar between AB (27% ± 0.1%) and CP (25% ± 0.1%) groups. EMG amplitude and frequency changed similarly in all muscle groups tested, in the CP and AB groups.</td>
</tr>
<tr>
<td>Silva et al. (^{29[I]})</td>
<td>10 male, 4 female</td>
<td>Athletics</td>
<td>VI, LD, Athlete guides</td>
<td>Self-reported musculoskeletal complaints and muscle strength assessed 3 times over a year before competition</td>
<td>Knee flexor and extensor muscle strength sig ↑ in both limbs at the second and third assessments compared to the first. Muscle imbalance was associated with knee and thigh complaints.</td>
</tr>
<tr>
<td>Taboga et al. (^{12[T]})</td>
<td>12 male, 5 female</td>
<td>Sprinting</td>
<td>AB, UL TTA</td>
<td>Two straight, CW curved and CCW curved sprints</td>
<td>TTA sprinters ran 3.9% slower with their affected leg on the inside compared with the outside of the curve. Stride length reduced in both curve-running directions, stride frequency reduced only on curves with the affected leg on the inside.</td>
</tr>
<tr>
<td>Hobara et al. (^{30[T]})</td>
<td>59 male and female</td>
<td>Sprinting</td>
<td>UL TTA</td>
<td>Analysis from publicly available Internet broadcast of Paralympic and International 200 m races</td>
<td>No significant differences in race times between left and right side amputees were found.</td>
</tr>
</tbody>
</table>

AB = Able-bodied; BL = Bilateral; CoM = Center of Mass; CoP = Center of Pressure; CP = Cerebral Palsy; CW = Clockwise; CCW = Counterclockwise; EMG = Electromyography; FPV = Foot Placement Variability; LD = Limb Deficiency; ML = Mediolateral; PO = Power Output; TD = Touch Down; TFA = Transfemoral Amputation; TO = Take-Off; TTA = Transtibial Amputation; UL = Unilateral; VI = Visually Impaired.
<table>
<thead>
<tr>
<th>Study</th>
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<th>Outcome</th>
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<tbody>
<tr>
<td>Dingley et al.</td>
<td>14 [T, I]</td>
<td>ID, VI, CP (n=3), LA, SS</td>
<td>6-wk strength training program. Outcome measure - 50-m time trial and timed dive starts</td>
<td>50-m time trials improved 1.2% ± 1.5%. Mean power ↑ 6.1% ± 5.9%, acceleration ↑ 3.7% ± 3.7% during the start, improved start times to the 5-m (5.5% ± 3.2%) and 15-m (1.8% ± 1.1%) marks.</td>
</tr>
<tr>
<td>Dingley et al.</td>
<td>27 male, 28 female</td>
<td>VI, ID, CP, LBI, UBI, stroke, SS</td>
<td>330 Swim starts collected at national training camps between 2008-2012</td>
<td>Regardless of disability, free-swim velocity is a priority area for improving swim-starts.</td>
</tr>
<tr>
<td>Dingley et al.</td>
<td>13 male, 15 female</td>
<td>VI, ID, LBI, UBI, CP, SS</td>
<td>Full anthropometric profiles estimated muscle mass and body fat. Swim-bench ergometer quantified upper-body power production, 100 m swim performance.</td>
<td>Correlations between ergometer mean power and swim performance ↑ with degree of disability. In no disability and LSD females greater muscle mass was associated with slower velocity (r=0.78 ± 0.43 and r=0.65 ± 0.66 respectively) and vice versa.</td>
</tr>
<tr>
<td>Fulton et al.</td>
<td>8 male, 4 female</td>
<td>CP, LA, AA</td>
<td>Inertial sensors and video-recordings during maximal-effort 100m free-style swim and 100m freestyle kicking-only.</td>
<td>Inertial sensors were a valid and reliable estimate to quantify changes in kick count and rate in freestyle swimming.</td>
</tr>
<tr>
<td>Fulton et al.</td>
<td>8 male, 6 female</td>
<td>CP, LA, AA, SS</td>
<td>Inertial sensors during 100m freestyle swim and 100m freestyle kicking-only trial before and after WCh.</td>
<td>145 ± 39 kicks for swim and 254 ± 74 kicks for kicking-only trials. Kick rate 124 ± 20.3 kicks/min for swim and 129.6 ± 14 kicks/min for kicking-only trials.</td>
</tr>
<tr>
<td>Fulton et al.</td>
<td>9 male, 3 female</td>
<td>CP, LA, AA, VI</td>
<td>Kick rate, dynamometer to assess towing speed, force-platform to assess net force at the start</td>
<td>When peak speed↑, active force↑, while kick rate remained. Net force↑ when larger kicking, whereas kick rate↓.</td>
</tr>
<tr>
<td>Oh et al.</td>
<td>69 male, 44 female</td>
<td>Multiple</td>
<td>Electro-mechanical towing device and load cell - passive drag force during 2012 PG</td>
<td>Passive drag ranged from 24.9 - 82.8 N. The current classification system does not always clearly differentiate between swimming groups.</td>
</tr>
</tbody>
</table>

AA = Arm Amputation; BL = Bilateral; CP = Cerebral Palsy; HSD = High-Severity Disabilities; ID = Intellectual Disability; LA = Leg Amputation; LBI =
Lower Body Impairment; LSD = Low-Sevility Disabilities; PG = Paralympic Games; PD = Physical Disability; SS = Short Stature; UBI = Upper Body Impairment; VI = Visually Impaired
<table>
<thead>
<tr>
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</tr>
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<tbody>
<tr>
<td>Baur et al.</td>
<td>Cycling</td>
<td>Incomplete SCI (TH 11)</td>
<td>LC3</td>
<td>15 s maximal isokinetic test (70 rpm, 90 rpm, 110 rpm) on a bicycle ergometer with individual (IO) and everyday orthoses.</td>
<td>IO suitable for high external (399 W at 90 rpm) loads in cycling, without negatively influencing muscular activity pattern during pedaling.</td>
</tr>
<tr>
<td>Brüggeman et al.</td>
<td>Athletics (sprints)</td>
<td>One BL TTA, 5 AB. 400 m performance matched</td>
<td>na</td>
<td>Running kinematics and kinetics during maximum speed running.</td>
<td>TTA total body kinetics ↓ mechanical work during stance phase vs. AB. ↓ hip and knee joint kinetics and higher ankle joint power vs. AB. ↓ energy loss at the prosthetic ankle vs. AB ankle.</td>
</tr>
<tr>
<td>Buckley</td>
<td>Athletics (sprints)</td>
<td>UL TTA (n=4) and TFA (n=1)</td>
<td>na</td>
<td>Video recordings of the prosthetic and sound limb during sprints. Sagittal plane hip, knee and ankle kinematics.</td>
<td>TTA and AB athletes showed a pattern of stance flexion-extension for both limbs. For the prosthetic limb (TFA) the knee was fully extended before and during stance) compared to the sound limb and AB.</td>
</tr>
<tr>
<td>Buckley</td>
<td>Athletics (sprints)</td>
<td>2 UL TTA</td>
<td>na</td>
<td>Repeated maximal sprint trials using Sprint Flex or Cheetah prosthesis.</td>
<td>Subject 1: ↑ hip extensor moment on the prosthetic limb and ↑ concentric work using either prosthesis. ↑ total work using Sprint Flex. Subject 2: ↑ extension moment at the residual knee and ↑ in total work using either prosthesis.</td>
</tr>
<tr>
<td>Costa et al.</td>
<td>Athletics (wheeling)</td>
<td>Charcot-Marie Tooth, type II (neuropathic disease)</td>
<td>T52</td>
<td>Biomechanical and physiological aspects of wheelchair propulsion.</td>
<td>Linear-direct relationship of wheelchair velocity with stroke frequency, but a linear-inverse relationship with push time. Bigger hand rims (0.37 m) ↑ stroke frequency while push time ↓. HR ↑ with velocity and was affected by handrim diameter (↓ at smaller diameters , ↑ at bigger diameters). A sig interaction between handrim diameter and wheelchair velocity.</td>
</tr>
<tr>
<td>Pradon et al.</td>
<td>Athletics (Long Jump)</td>
<td>Below elbow amputation</td>
<td>F46</td>
<td>3 long jumps. One with no mass added, one with 0.3 kg added and one jump with 0.4 kg added to the prosthetic wrist.</td>
<td>Long jump distance reduced when mass added. No change in horizontal velocity during run-up. Adding 0.4 kg mass greatly perturbed long jump take-off parameters.</td>
</tr>
</tbody>
</table>
### Table 4 Continued

<table>
<thead>
<tr>
<th>Study</th>
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<th>Impairment</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Weyand et al. 39</td>
<td>Athletics (sprints)</td>
<td>One BL TTA, 4 AB . 400 m performance matched</td>
<td>na</td>
<td>Metabolic EE during running, sprint endurance, sprint mechanics all performed on a treadmill.</td>
<td>TTA: metabolic cost of running similar to AB, sprint endurance comparable to AB, ↑ contact time (+14.2%), ↓ aerial time (-34.5%), ↓ stance-average vertical forces (-21.7%).</td>
</tr>
</tbody>
</table>

AB = Able-bodied; BL = Bilateral; EE = Energy Expenditure; HR = Heart Rate; na = Not Available; RPM = Rounds Per Minute; SCI = Spinal Cord Injury; TFA = Trans-Femoral Amputee; TTA = Trans-Tibial Amputee; UL = Unilateral
Figure 1 – Flow chart for literature search