Clinical Perspectives in Research and Product Development

Biomechanical analyses of the performance of Paralympians: From foundation to elite level

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Summary

Biomechanical analysis of sport performance provides an objective method of determining performance of a particular sporting technique. In particular, it aims to add to the understanding of the mechanisms influencing performance, characterization of athletes, and provide insights into injury predisposition. Whilst the performance in sport of able-bodied athletes is well recognised in the literature, less information and understanding is known on the complexity, constraints and demands placed on the body of an individual with a disability. This paper provides a dialogue that outlines scientific issues of performance analysis of multi-level athletes with a disability, including Paralympians. Four integrated themes are explored the first of which focuses on how biomechanics can contribute to the understanding of sport performance in athletes with a disability and how it may be used as an evidence-based tool. This latter point questions the potential for a possible cultural shift led by emergence of user-friendly instruments. The second theme briefly discusses the role of reliability of sport performance and addresses the debate of two-dimensional and three-dimensional analysis. The third theme address key biomechanical parameters and provides guidance to clinicians, and coaches on the approaches adopted using biomechanical/sport performance analysis for an athlete with a disability starting out, to the emerging and elite Paralympian. For completeness of this discourse, the final theme is based on the controversial issues on the role of assisted devices and the inclusion of Paralympians into able-bodied sport is also presented. All combined, this dialogue highlights the intricate relationship between biomechanics and training of individuals with a disability. Furthermore, it illustrates the complexity of modern training of athletes which can only lead to a better appreciation of the performances to be delivered in the London 2012 Paralympic Games.

Key words: reliability, classification system, sport performance, biomechanics, Paralympian

SC: ***Using one spinal cord injury related and one transtibial amputee as examples, what advice do you give to an athlete expressing an interest in participating in a sport?***

LF: I can only encourage all persons with a, so-called, disability to be involved in sport activities, adapted or not. Go for it! Various factors could make this experience rewarding. In my opinion, it is essential that participants find the right match between their physical abilities, personal preferences and access to local resources.

Paralympic sports are designed for individuals with amputation, spinal cord injury as well as visual impairment, cerebral palsy, learning disabilities and other forms of impairments (“les autres”). The good news is list of sports on offer can accommodate a range of physical abilities and classifications [1]. Some required minimal engagement like Boccia. Others are highly demanding like the Marathon. So, there are opportunities for individuals with all types and ranges of impairments [2].

The other good news is that these sports can accommodate a range of personal preferences: indoor versus outdoor, individual versus collective, dry versus wet, short versus long, summer versus winter, fine motor skills versus high physical engagements, etc. That includes sports like athletics, archery, wheelchair rugby, downhill ski, swimming, tennis, seated ice-hockey: you name it!

A sustainable involvement requires access to training facilities as well as partakers with some expertise in coaching, design of equipment, classification, physiotherapy, sport administration, etc. These initial choices might appear dompting at first glance. The International Paralympic Committee (http://www.paralympic.org/) provides official resources and links to National Paralympic Committees. This is a good starting point. Furthermore, there are plenty of user-group websites and countless blogs are available. All combined, this information will help to set motivation and suitable expectations to kick-start a fulfilling athletic experience.

SC: *Do you think ‘biomechanics’ offers a real added-value to sports performance of Paralympians?*

LF: I would love to say that biomechanists alone can generate radical new techniques or equipment leading to performance improvement. But, this is rarely the case. For example, the transition in high jump techniques from scissor to Fosbury flop passing by the eastern cut-off, western roll and straddle techniques, was mainly led by athletes and coaches although the biomechanical advantages of Fosbury flop are obvious with the benefits of insight.

Nonetheless, biomechanical analyses are critical to coaches and athletes because they provide comprehensive description and, eventually, explanation of the performance. Kinematics analyses can demonstrate that high-jumper’s body could clear the bar while his/her centre of mass could be passing below the bar. More importantly, these analyses can determine the distance between the position of the centre of mass, the body segments and the bar during clearance.

SC*: How does biomechanics act as a tool to support evidence-based training?*

Biomechanical analyses are used to assess how changes in core mechanical parameters of sports techniques, strength and conditioning as well as design of equipment influence the performance. They are, also, used to identify outskirt parameters that can potentially lead to injuries and/or improvements. This information is essential to guide the decisions made by coaching teams [3].

In principle, these analyses can rely on the kinematic (e.g., range of movement, position, velocity, acceleration, momentum), dynamics (e.g., contact external forces and moments, impulse) or kinetics (e.g., joint moments, power and mechanical work) data collected separately or simultaneously. However, in the reality, the decisions made by coaching teams are mostly guided by kinematic information. I will go even further by arguing that over the last ten years, access to high quality and easy-to-use video information has strongly contributed to place biomechanics, more particularly kinematics, analyses of the performance at the heart of evidence-based training programs [4].

SC*: So how does evidence-based training influence day-to-day training?*

LF: In most cases, coaching teams rely on two forms of biomechanical analyses. The first one is often referred to as a *"qualitative"* analysis. In this case, the performance is described using words and very simple tools provided by the video analysis software packages. It is a great way to facilitate self-observation. I have used it either in-between drills and/or during post-training debriefings (**Figure 1**). This is important because in the vast majority of activities are too rapid to be fully comprehend with naked eye. Furthermore, self-observation is essential for athletes with a cerebral palsy or spinal cord injury as their proprioception might be limited or even misleading [4].

A B

Figure 1. Lay out (A) and set up (B) of portable motion analysis system used to facilitate evidence-based training of Australian emerging and elite stationary throwers.

Coaching teams can also gather information from, so-called, *"qualitative"* analyses. Here, the performance is described by data presented mainly in table and graph formats. This requires a wider range of measuring device (e.g., accelerometers, high-speed video cameras, 3D motion analysis systems, forces plates, load cells), more constraining recording conditions to warrant accuracy and specific software packages. Typically, these measurements are conducted during purposeful and carefully planned data collections sessions taking place in dedicated facilities (**Figure 2**). The data analysis is labour intensive. Thus, the extraction of meaningful results can take up to several weeks. So, the benefits of this approach are not as immediate. Nonetheless, it contributes to more in-depth reflection.

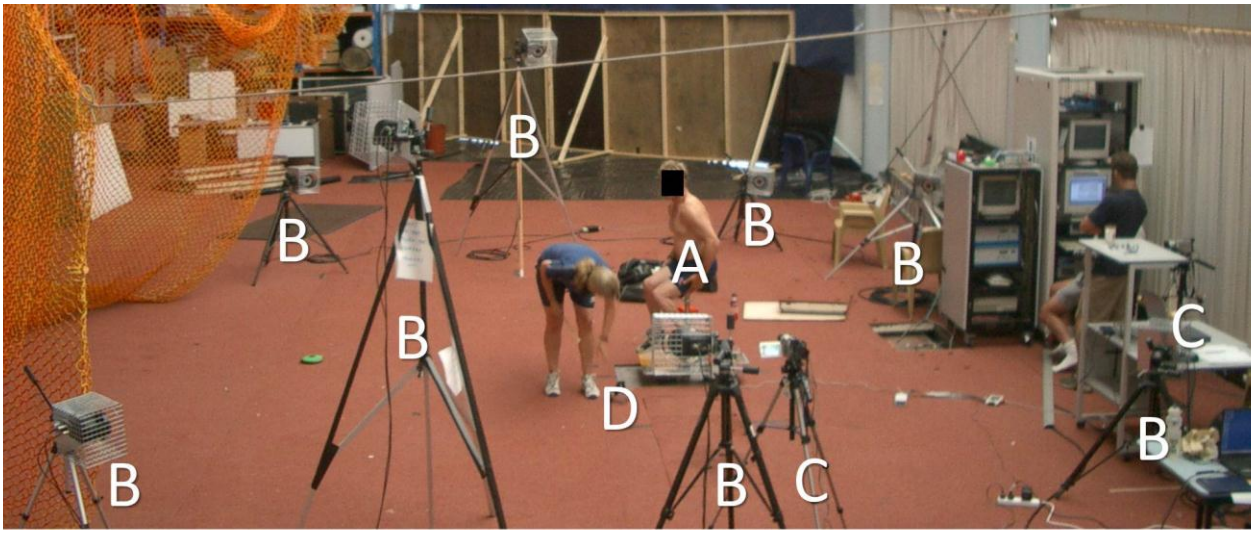

Figure 2. Performance analysis of stationary thrower (A) in the motion laboratory of Australian Institute of Sports' including the 8-camera 3D motion analysis system (B), two high-speed video cameras (C), a force plate (D) and two load cells.

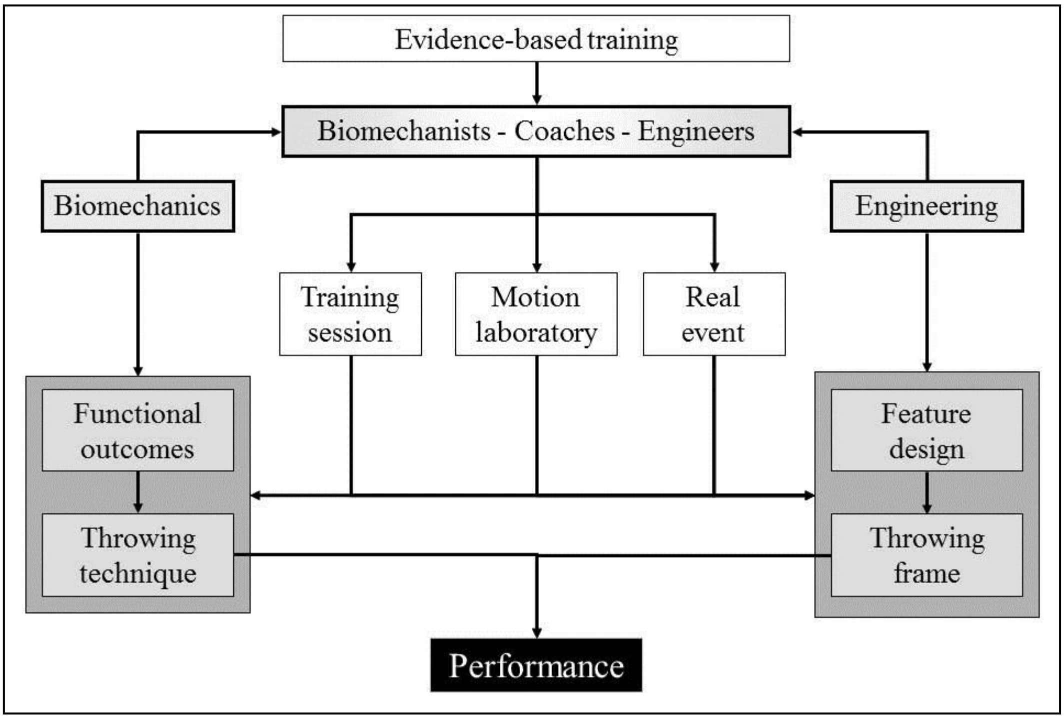

Figure 3. Procedure supporting evidence-based training aiming at improving performance of seated throwers.

SC: *What are the specificities of evidence-based training programs for Paralympians?*

The general principles underlying the evidence-based training mentioned above are applicable to Paralympians and able-bodied athletes alike. However, I will argue that biomechanical analysis of the performance is far more critical to Paralympians on two accounts (**Figure 3**).

Impairments, disabilities, illnesses or accidents rarely affect individuals in exactly the same way. Consequently, variations of basic functional abilities are greater between Paralympians than able-bodied athletes. Therefore, there is a greater need for individual assessments of the functional outcome. Also, there is more room for exploring avenues of technical developments. Furthermore, such assessments might lead to an evidence-based classification of the participants [5-16].

Another fascinating facet of adapted physical activities is the use of specific sport equipment which include wheelchair, bicycles, throwing frame, and so on. Currently, the construction of each individual equipment is mainly driven by an empirical approach relying on the feedback from coaches and athletes, apparent functionality and sensations of comfort as well as access to local resources. This means that there is a need for more biomechanics supporting evidence-based design of this equipment [3].

SC: ***How can biomechanics and performance analysis aid in reducing the perceived risk of injury in Paralympians?***

LF: At first glance, one could presume that athletes with a disability are more prone to injuries. However, very little evidences support this hypothesis [17-22]. Most studies are demonstrating the rate of injuries of athletes with disability comparable to able-bodied athletes.

In principle, biomechanical analyses have the potential to reduce intrinsic and extrinsic risks factors related to injuries corresponding to factors that affect the tolerance and the characteristics of the load applied to the tissues within the athlete, respectively. In particular, biomechanics can help to minimize risks factors related to movement technique and interaction with equipment.

Assessments of the range of movement during training can determine if the technique promotes excessive joint constrains that are beyond the acceptable and sustainable limits of the athlete's actual anatomical and physiological abilities. Customization of the throwing frame is critical as some athletes may be prone to pressure sores due to time spent on frame for training purposes. Furthermore, self-observations and comprehensive evaluations can help to do less but may be more focused and efficient drills, subsequently, reducing the opportunities for fatigue-related injuries.

SC: ***Within the field of biomechanical analysis of sports performance, how important is collaborative team work?***

LF: I was lucky to be included in the coaching team of the seated throwers of Australian Athletic Paralympic team as Sport Biomechanics between 2000 and 2009 under the lead of Alison O'Riordan, Head Coach of seated throwers and Scott Goodman, Head Coach of the Athletics team. To the best of my knowledge, I think Australia was the only country worldwide to embed a biomechanist in its staff.

This gave me the opportunity to participate and collect data during regular training sessions, training camps, as well as several local, national and international competitions including 2 IPC World Championships (i.e., Lille, Assen) and 3 Paralympic Games (i.e., Sydney, Athens, Beijing (**Figure 4**)). Some of my missions included making recommendations about the throwing technique and the design of the throwing frame in the framework of an evidence-based training (**Figure 3**). This is when I realized how much biomechanical analyses of the performance of athletes with a disability are becoming a multidisciplinary effort. They involve input not only from coaches and athletes but also from biomechanists, engineers, classifiers, officials, referees and even sport administrators. Modern and visionary coaches, like Alison O'Riordan are becoming architect and conductor of *"coaching team"* in charge of synthesising and harmonizing critical information.

A B

Figure 4. View of the camera from de side (A) and front (A) collecting kinematic data during a seated shot-put throwing event at the Beijing 2008 Paralympic Games.

SC: ***What are the emerging new technologies in the field of biomechanical analyses of sports performance for athletes with a disability?***

LF: Biomechanical analyses of athletes with a disability are currently driven by affordable, discreet, highly performing and easy–to-use technologies capable of recording and analysing the movement. The range of commercial products, including device and software, on the market is amazing.

Handheld equipment such as cameras has been coaches' best friend for over a decade. Nowadays, high-speed and digital footage can be manipulated a lot easier thanks to simple media player or more advanced video analysis software packages. More importantly, a number of "on-board" device are emerging. Accelerometers, load cells, GPS, odometers, to name only a few, are now commonly attached to the athlete's body. Recordings are taking place not only during training but even during competition in some cases.

Like any other facets of society, Smartphones are currently revolutionizing biomechanical analyses of sports performance. Their advanced computing ability pools connectivity (e.g., Bluetooth, internet), devices (e.g., high-resolution digital video camera, gyroscope, GPS) and software (e.g., Apps, Applications Programming Interface) into a one single device capable of recording, analyzing and transmitting motion-related information. All that is a handheld device! There is already a bunch of apps available looking at range of movement, intersegment angles or implement's trajectory, for example.

Coaches might be using Smartphones to assess the movement the same way a doctors check the heart bits with a stethoscope or orthopaedic surgeons assess a fracture with an X-ray! All combined, these instruments could make the unknown visible. Therefore, they have the potential to change dramatically not only the perception but also the consensus in the field of biomechanics of Paralympians.

SC: ***How can new technology impact on evidence-based training analyses? Is there a possible cultural shift?***

LF: This emergence of training-friendly instruments could generate significant cultural shifts in ways athletes are trained. Athletes are no longer going into motion analyses laboratories to be assessed by sport biomechanists only. Some performance assessments are also conducted directly by the coaches and athletes on a daily basis during training. There is an *"instrumentalisation"* of athletes so that information can be collected during the actual performance. This means that the usual paradigm underlying biomechanical analyses of the performance relying on the dichotomy between qualitative and quantitative approaches is no longer relevant. All analyses are more likely to be qualitative by nature.

SC: ***Given your previous response and comments, is there likely to be a possible end of empirical assessment of performance analysis?***

LF: I think simple visual observations will always be useful although they might not be valued as much. Consequently, I believe a new paradigm is currently emerging contrasting at-glance and in-depth analyses. At-glance analyses are supported by a range of new training-friendly instruments than can provide immediate, simple and 2D but not always validated and accurate information. Complementary in-depth analyses could be conducted in dedicated facilities such as motion analysis laboratories fitted with 3D motion analysis systems and other dynamics equipment to provide accurate and comprehensive description of the performance that might be slightly altered.

SC: ***Can and should sport coaches subsume an integrated role as coaches and laboratory technicians?***

LF: Training-friendly instruments provide blunt information. Coaches are needed to determine what to look for and which data is relevant. At this stage, I believe coaching remains a craft that relies on the *"expert eye"* combining intuition, experience and tangible information. However, adoption of new technologies might promote the importance of the *"instrumented eye",* where training decisions might be based on evidences rather than subjective information.

Instrumentalisation of athletes is also contributing to an otherwise surprising trend: *teletraining*. Daily face-to-face contacts and live observations of an athlete during training is no longer a pre-requisite for successful coaching. Instead, video files and other data reporting the workload achieved could be sent to a remote coach. Technical comments and instructions can be exchanged using shared software platforms.

SC: ***In order to claim scientific credibility, accurate measurement represents a fundamental element to all aspects of human movement analysis (e.g. clinical, sport). Taking the words of Rothstein who states that 'Reliability of measurement is the hallmark of any scientific endeavor', how confident are you with the information and data gleaned from the current systems and interpretation (i.e. intra and inter-rater reliability of observers)?***

LF: By definition, training-friendly device provides a signal regardless of the way it is used. However, the protocol matter. A poor implementation might lead to unreliable information [23]. For example, an accelerometer stuck on the sleeve of a T-shirt covering the throwing wrist might determine poorly the hand's acceleration because of the sliding between the skin and the sleeve. Therefore, the reliability of the information deriving from these instruments will depend on the coaches' and athletes' basic and applied understanding of instrumentation as well as kinematics, dynamics and kinetics all together. This knowledge is essential to determine how much the data can be trusted and caution in the interpretation must be applied.

SC: ***Do you think 'instrumentalisation' is a plus or a burden for both athletes and coaches?***

LF: It could be either a burden or a blessing depending on the level of interest and trust the coaching team put in these measures. Once, I have tried to use all together two video cameras and two transducers embedded into the foot straps of an adjustable throwing frame. This setup aimed at determining the optimum foot position during stationary throwing event (**Figure 5**). The recording took place during training session a few months before Athens 2004 Paralympic Games. The recording protocol had to be modified half way through the session as the data observations in-between attempts or drills were deemed too disruptive. The coach felt the extension of the recovery time was compromising the aims of the drills them-selves. Athlete also reported focusing more on the data than on the theme of the drills. So, it was decided to carry the measurement but postpone the observation to the post-training debriefing.

So, the abundance of equipment and too frequent reference to the output can be invasive and eventually counterproductive. Another downside of this equipment is that they might give a false impression of conducting scientific measurements, particularly when the, sometimes too restrictive, terms of use are violated. However, I have experienced that a parsimonious use of training-friendly equipment can be extremely informative and productive. I think it is a little bit like school exams to verify acquisition of knowledge or medical check-ups to follow health status.

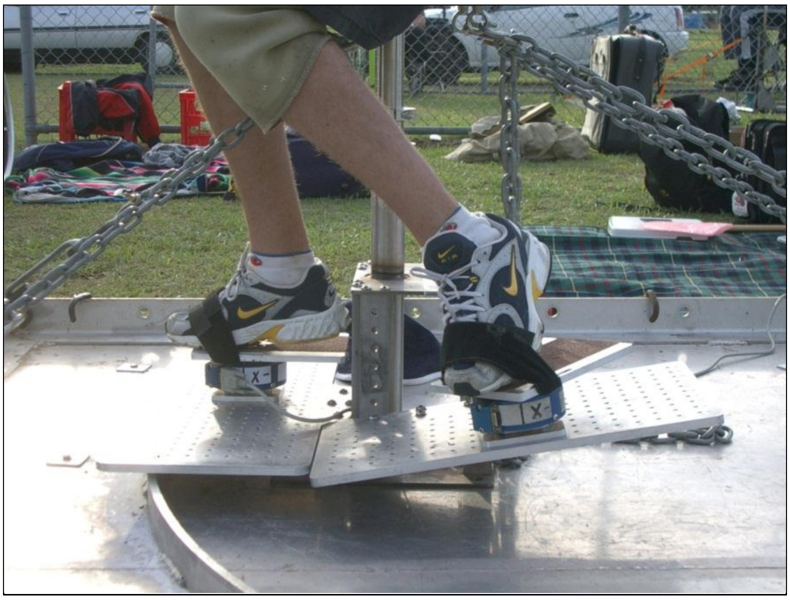

Figure 5. Load cells fitted within an adjustable throwing frame measuring the forces and moments applied on the feet during stationary throwing event.

SC: Incidentally, I am interested to know more about the feet position. Why does it matter? Have you been able to find this optimum position for this athlete? Could you results be generalized to other athletes?

LF: The importance of the feet positions relies on the validity of the concept of transfer of linear and angular momentum from one segment to the next. The movement is facilitated when the heavier segments move first followed successively by the lighter ones. Typically, athletes in F33 and F34 classes have limited extension in their lower limb. However, the foot position is critical to determine how the ground reaction forces and moments are transmitted through the lower limb to action the trunk during the course of the throw. So, it important to find feet positions that create the most favorable displacements of the trunk and ultimately the release of the implement.

The load cells embedded into the throwing frame helped to identify several combinations of the loading profiles that could possibly led to better performance. The measurements certainly showed that the loading profiles were different for each athlete.

I am always reluctant making generalizations based on data from a small cohort. Furthermore, analyses of feet positions of all athletes competing in the F30s classes during the Assen 2002 IPC World Championships revealed weak correlation with the performance [24]. These results confirms that feet positions might be athletes dependent, highlighting the need for individual assessments to determine optimum feet positioning.

SC***: Over the years there has been much discourse and debate on the role of kinematic 2-dimensional (2D) versus 3-dimensaionl (3D) analysis. Many readers will be aware of the practical and theoretical limitations of both approaches, but in terms of your experience what are your thoughts?***

LF: Let me share an anecdote with you. My involvement in sport biomechanics of Paralympians started in early 2000, after a conversation with Dr Keith Gilbert, a colleague at Queensland University of Technology (QUT). As the future Chef de Mission of the Australian Paralympic Team at the Sydney 2000 Paralympic Games, Keith mentioned that there might be some research opportunities with the Australian athletes. Chris Nunn and Scott Goodman, coaches of the Paralympic athletic team welcomed some of my research proposals. They facilitated further opportunities to work together around the performance analysis of stationary throwers. They suggested that I tried to collect some data during the upcoming Paralympic Games in Sydney. This opportunity was too good to be missed!

Back then, I had limited experience in sport with disability. However, I was well aware of the uniqueness of collecting data under these exceptional circumstances. So, I was determined to make the best out of it. That included collecting 3D kinematic data. My doctoral work, completed in France and Canada a few years before, focused heavily of 3D kinematic analyses of the locomotion of individuals with lower limb amputation. In Montreal, I had been trained on one of the most advanced 3D motion analysis system at the time. So, I thought I had sufficient basic and applied knowledge to face the challenges associated with the recording of 3D data during live outdoor event.

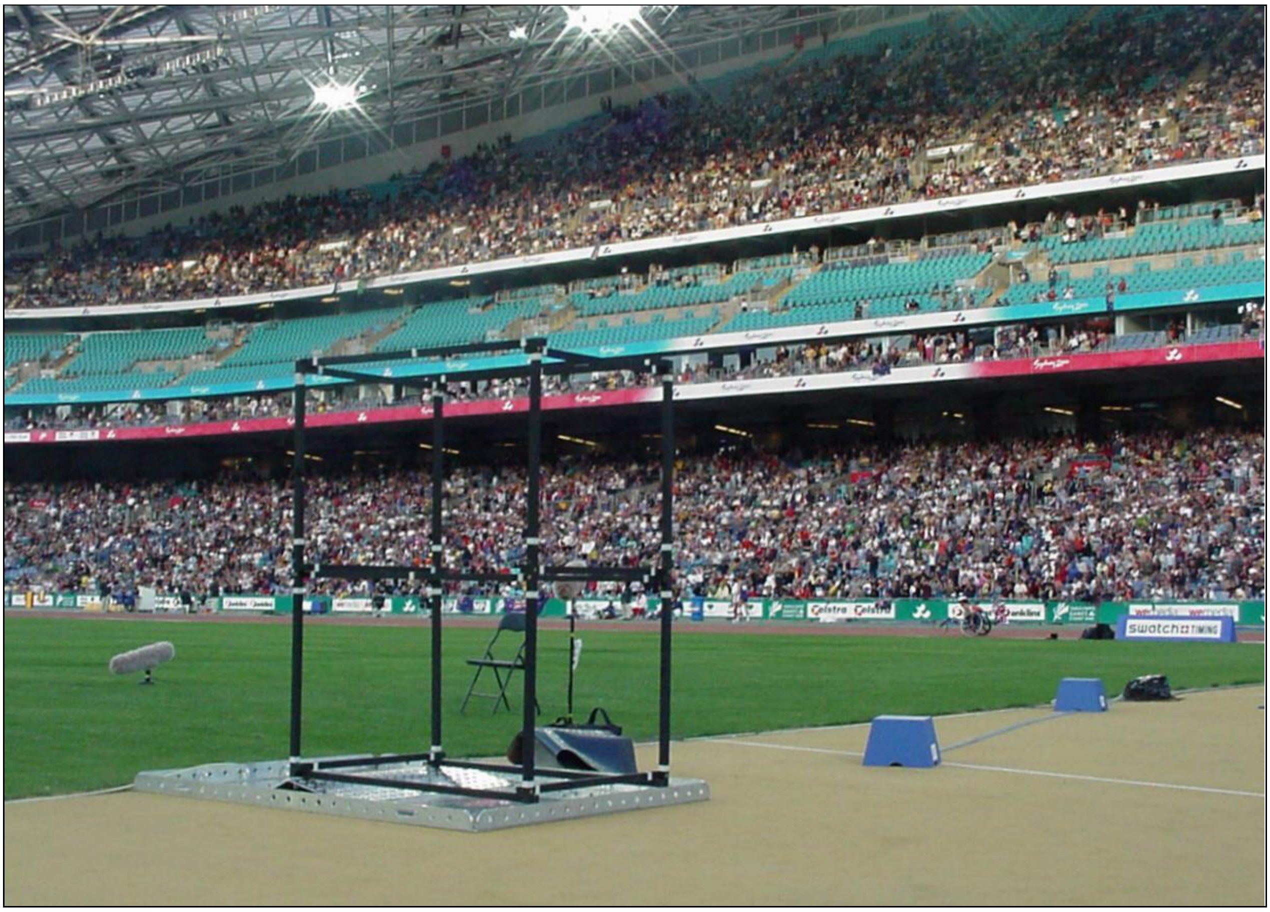

Figure 6. Calibration frame used for 3D reconstruction of kinematic data collected during world-class events.

I knew the calibration would be tricky. So, I designed a portable calibration frame featuring all the necessary reference points (**Figure 6**). The second problem to overcome was the tracking of body landmarks. In conventional experimental settings, reflective markers are placed on the participant during recording. The path of each marker is detected and reconstructed in 3D by the motion analysis software. No need to say that placing markers on the athlete was not an option during the Games. So, I had come to term with the long hours I would have to spend on locating body landmarks manually, frame after frame. I had written a specific piece of software to do so in the reasonably efficient way. Several pilot studies were successfully completed at the Sydney Academy of Sports and QUT. I felt as prepared I as could be when I was looking up to the cauldron inside the Homebush Bay stadium before the first stationary throwing event.

Well… reality had truly set in by the end of the day! I had been able to place the cameras on the front and the side of the thrower as I wanted. The problems of power to feed the cameras had been solved rather quickly. Both issues were addressed with a great support of the organisers and TV crews. Finally, I had been able to calibrate before and after the event. Calibration is a pivotal step in experimental settings. The number of experimenters in the laboratory is kept to a minimum. Everyone is focused and cautious not to interfere with the process. It is a little bit like taking an X-ray: don't breath, don't move! Here, this task was completed surrounded by about twenty people around the pit and 60,000 spectators: a Guinness World Records in its own!

All the intrinsic aspects of the measurements went by the book. However, I had simply overlooked the context of the recording. The throwing pit was crowed! The view of the camera was occasionally obstructed in-between and during the attempts by objects or people passing by such as officials, athletes, referees, TV crews, etc. More importantly, I had no certainty that none of the cameras were moved in between calibrations. I carried on with the same procedure for the rest of these Games. Fortunately, a fair number of attempts were eligible for 3D reconstruction. The other ones were analysed through two bi-planar analyses including the sagittal and frontal plans.

Since, I have found ways to go around these perturbations [23, 25, 26]. However, this experience taught me a valuable lesson that helped me a great deal in the development of biomechanics tools for evidence-based training of stationary throwers. It is essential to make sure that the instrumentation and recording set up fits nicely with the practical circumstances surrounding the recording.

SC: ***In terms of performance analysis of multi-level Paralympians is there scope and validity for the introduction of a one-fit-all model?***

LF: This is an important question because I believe that a successful integration of biomechanical information into a training program seats on proposing analyses matching the needs of coach and athlete. Indeed, the expectations of newcomer, emerging and elite Paralympians are different. This can be illustrated by the performance analysis of stationary throwers (**Figure 7**).

SC: ***Before detailing the performance analysis for athletes with different levels, it will be useful to describe briefly what is a "stationary throw"?***

LF: Seated or stationary throwers participating in shot-put, discus and javelin events belong to the F30 and F50 classes including mainly athletes with cerebral palsy, spina bifida, amputation and spinal cord injuries. They all required an individual throwing frame anchored onto a plate. At first glance, a frame is a scaffold-like chair made of metal bars and plates welded together [27]. Athletes with the least physical abilities remain seated during the whole throw. Others with more abilities throw from a seating or standing position and release the implement standing up. Some use a rigid pole attached to the frame for balance and/or propulsion purposes. Others don't.

A typical throwing technique involves a few preparatory oscillations of the upper body prior release of the implement [3]. The performance corresponds the distance between the edge of the plate and the footprint left by the implement on the ground. The performance is pre-determined by the parameters of implement's trajectory at the instant of release, namely: the position in relation to the edge of plate, the angle and the speed (**Figure 8**) [28].

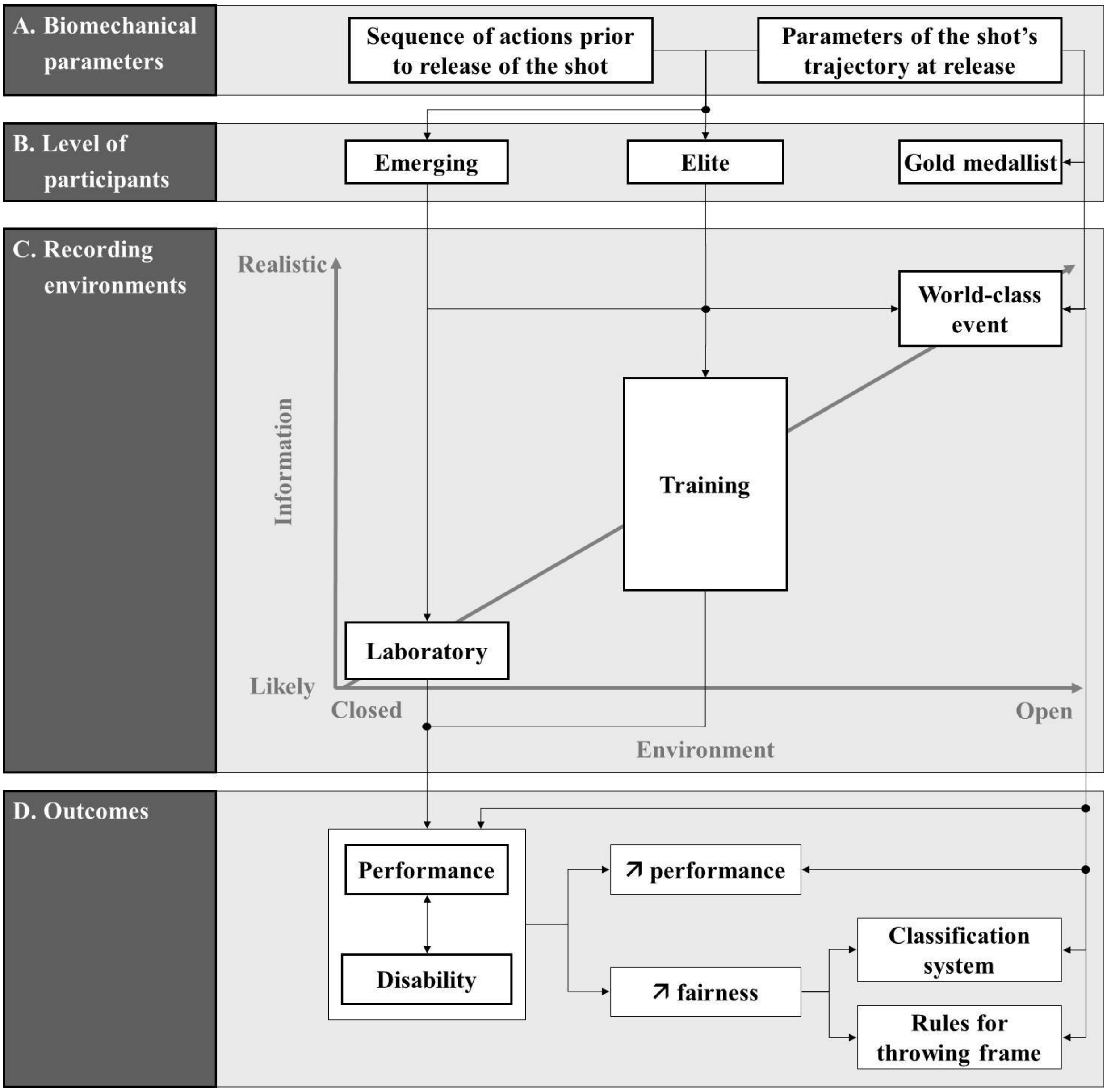

Figure 7. Overview of key factors determining the performance analysis of the seated throwers.

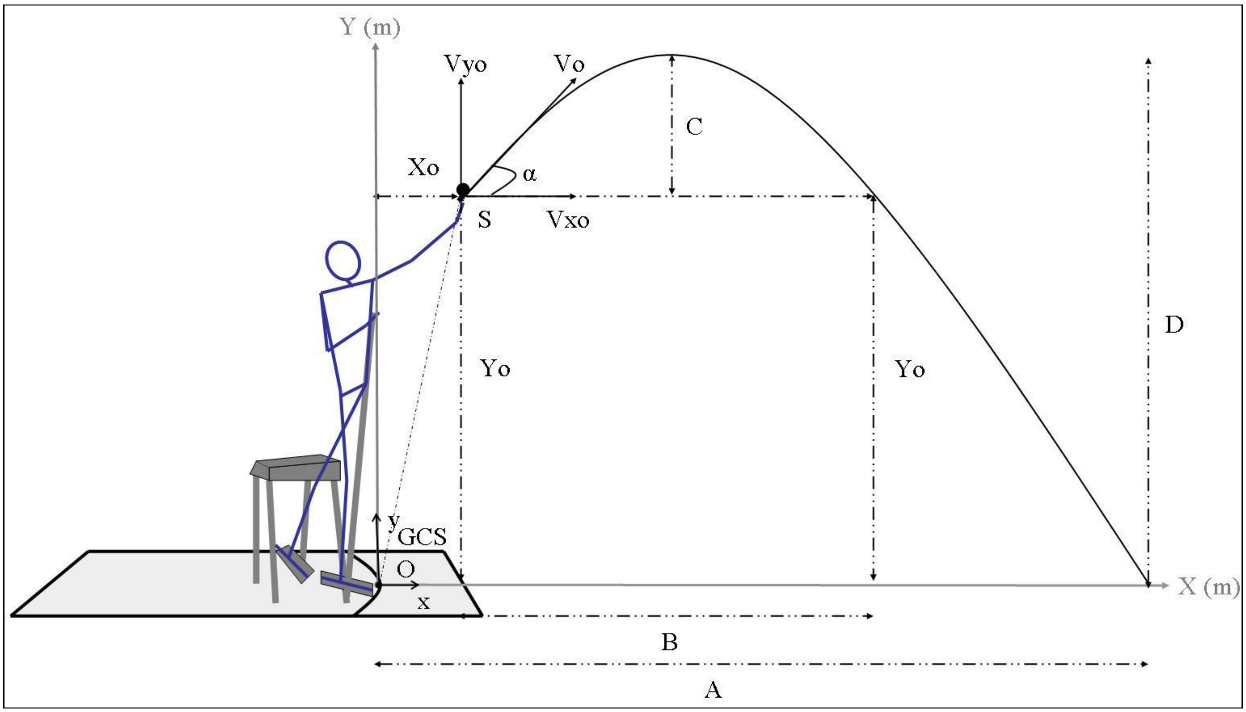

Figure 8. Initial characteristics of the trajectory of the put at the moment of release.

SC*: What are the key biomechanical parameters of the peformance of an athelete with disability?*

LF: This primary aim of performance analyses is to comprehend how these parameters are generated. Typically, the variables of interests are the sequence of actions prior to release (origin of performance) using spatial and temporal characteristics of backward and forward body movements, range of motion, linear and angular momentum of each segment, etc [10, 28, 29]. Eventually, the secondary purpose is to put forward modifications in throwing technique and/or in design of the frame susceptible to produce the most favorable parameters. In both cases, a good understanding of the interaction between the athletes and their throwing frame is critical (**Figure 9**) [4, 27].

The relationship between performance and throwing technique is fairly well described in several studies focusing on able-bodied throwers [20, 30-40] and seated throwers [2-4, 10, 28, 29]. However, the relationship between performance and the characteristics of throwing frame tend to be ignored despite its critical contribution to the performance [3, 27]. Some of my applied research as a Sport Biomechanics of the Australian Paralympic team under the lead of Alison O'Riordan revealed the nature of this contribution through the development of an adjustable throwing frame.

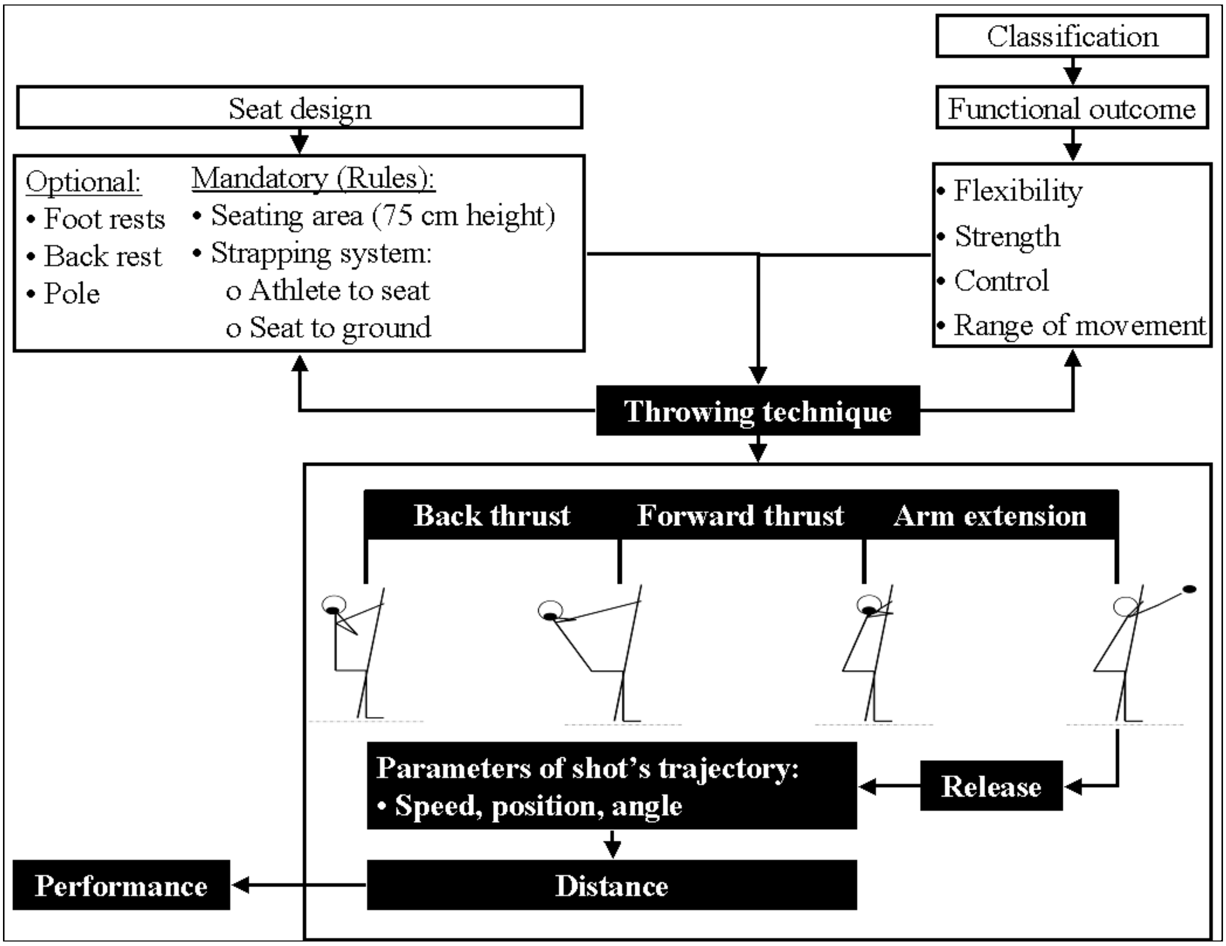

Figure 9. Factors influencing the throwing technique of seated throwers.

SC*: For athletes with a disability starting out in a sport, what approach would you suggest?*

LF: Typically, the room for improvement of newcomer athletes is large. It might be a matter of meters rather centimeters. Therefore, biomechanical assessments have to report important variations between performances requiring minimal level of accuracy. Initially, these assessments can be conducted using a Smartphone's camera. This is simple, practical and efficient! Footages can be visualized with any widely accessible media player on and off the field, during and after training for immediate and more in-depth feedback. The footages contribute to develop a sound technique. Here, coaches tend to have a holistic view of overall body shape. Is the sequence of transfer of momentum starts from the lowest and heaviest segments all the way to the hand during the course of the delivery?

I would expect self-observations have the additional benefits: increasing motivation. These footages are the living memories of progression pathways. So, archiving and visioning of regular footages is essential for athletes, the same way writers look back on early drafts of their books or musicians on initial sound track of a piece.

Another benefit, more removed from performance itself but equally important for individuals with a disability, might be anticipated: improvement of self-esteem. Individuals engaging in adapted sports activities might be coming for difficult walks of life. In some cases, illness or accident has led to complete review of one-self, including body image. Footage might facilitate a positive reorganization as they are the living proof of individual's ability. They highlight the term "ability" in the word "disability".

SC*: What approach would you adopt for emerging athletes?*

LF: Slightly more advanced assessments might require for emerging athletes. I found commercial motion analysis systems useful. I have used some featuring up to three video cameras recording independently or simultaneously also or via a laptop. The 2D or 3D displacements of the body segments are extracted and analyzed through specific software featuring key interactive tools, such as replay with slowing down motion, overlapping scenes, insertion of visual cues, etc. For example, throws of an athlete with different searing arrangements could be superimposed. Again, the footage can be analyzed on and off the field, during and after training for immediate and more in-depth feedback.

Self-observations, alone or with the coach, through the footages are particularly important for emerging athletes. They can contribute to readjust the disconnection between their sensations and actual movement if needed. I can report countless examples when stationary throwers with cerebral palsy in the F30s classes were surprised by the gap between the actual position of their throwing arm at release and the one they felt.

SC*: Does the same principles applied to elite Paralympians?*

LF: Expectations from biomechanical analyses of elite seated throwers are more specific. By essence, the aim is to improve the performance by a small but crucial percentage. Centimeters matter. So, the measurements must have a great deal of accuracy. The analyses are focusing on clearly identified and limited number of parameters. What is the load applied on both feet increasing when their positions change? Is a rotating handle on the pole modifies the position at release? Is a stiffer pole increasing the speed of release?

These questions might be only partially answered using basic motion analysis systems in conventional training facilities. This is why alternative biomechanical analyses are taking place in dedicated venues fitted with 3D motion analyses systems, forces plates and other specific sensors such as load cells, accelerometers or dynamometers (**Figure 2**). I have been privileged to coordinate some of the most advanced data collection in the motion laboratory of Australian Institute of Sports during the course of the development of ground breaking adjustable throwing frame prior the Athens 2004 Paralympic Games. The effect of different seating arrangements were assessed using simultaneously a 8-camera 3D motion analysis system, two high-speed digital cameras to record kinematic data along with one force-plate and two load cells to obtain dynamic data (**Figure 10**). That was amazing! I hope I will have a chance to conduct such comprehensive measurements again.

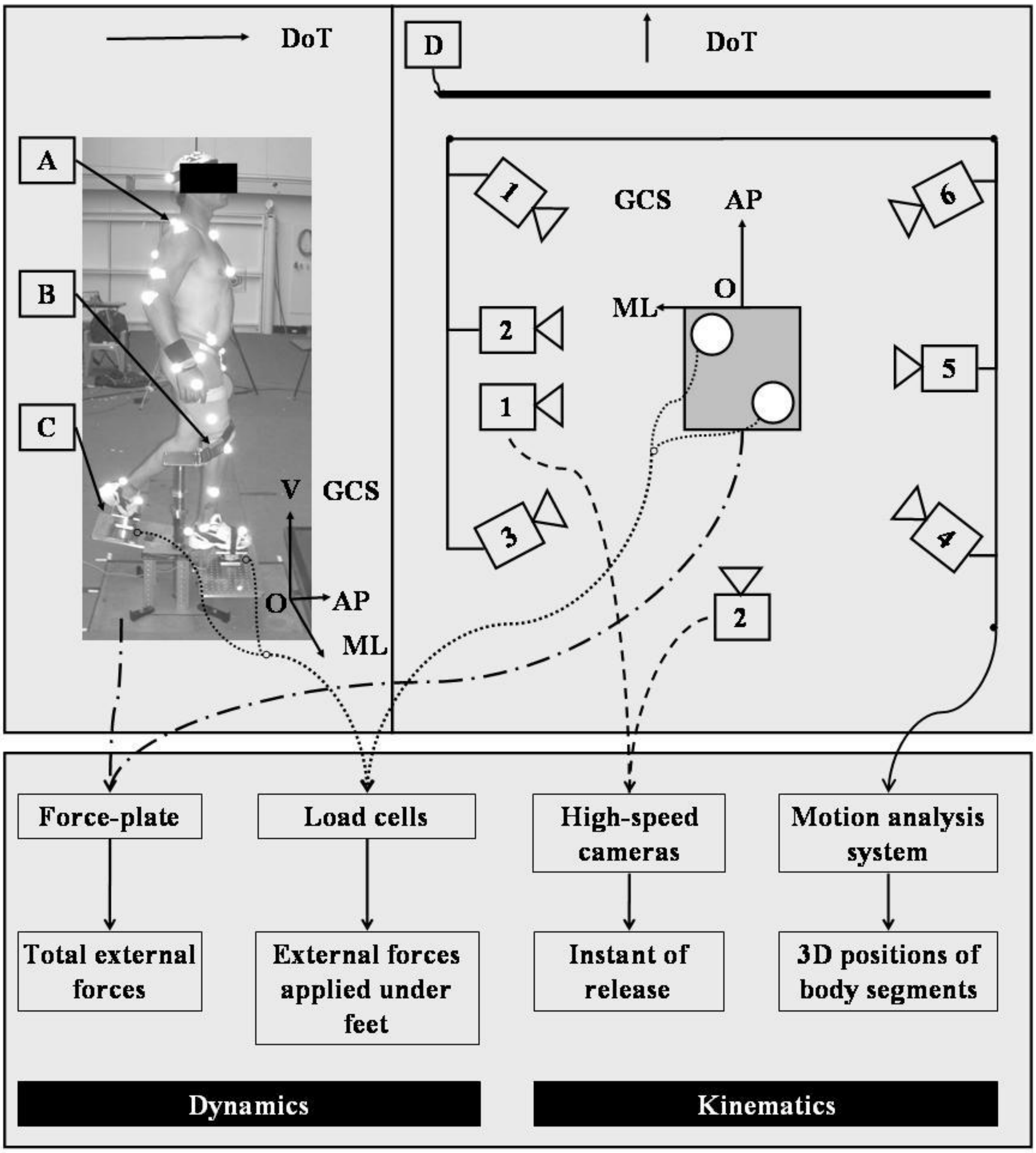

Figure 10. Schematic representation of the recording of kinematic and dynamics data to support evidence-based design of an adjustable throwing frame (GCS: global coordinate system, V: vertical axis, AP: antero-posterior axis, ML: medio-lateral axis, DoT: Direction of the throw).

SC: Adjustable frames are used for throwers with a disability, how can they help improve performance?

I believe it is fair to say that Alison O'Riordan and her team have set up new standards in design of throwing frame. Australian throwers have been using it since Athens. Their overall performances are following an upward progression. Some won medals in world-class events with it.

However, performance is multi-factorial. Alison O'Riordan had brilliantly put in place multiple concurrent performance enhancement procedures. Consequently, one needs to be cautious about the direct contribution of the frame. At best, we could only conclude that it was not counterproductive. Personally, I believe that the Australian coaching team has greatly benefited from the reflective process underlying the design of the frame. This it-self is a drive for performance enhancement.

SC*: The use of assistive devices seems to be an unrelenting controversial area within the world of sport as a whole, and is particularly apparent within sport and disability. Given your experience and past involvement with the Australian Paralympic team, what are your thoughts on this?*

LF: This is a difficult question. Indeed, I believe this might be one of the critical issues facing the governing bodies of adapted physical activities. It is commonly acknowledged that the performance results from the interaction between the athlete and the sport equipment involved.

I have used the term "sport equipment" but your question is referring to "assistive device". In this context, both terms are interchangeable. In principle, they should describe two separate categories with specific attributes. Sport equipment enables and, eventually, improves performance. Assistive device compensates for loss of function. This distinction cannot be made in the case of devices used in Paralympic sports. Some equipment fit into one category more than the other. Most belong to both. The prosthesis of the sprinter with lower limb amputation is an assistive device replacing the missing limb. However, the blade fitting the prosthesis is specifically designed to perform in sprinting events. This ambiguity adds enormous complexity to the debate [16, 41].

The question is how the interaction between the athlete and the equipment should be regulated? More precisely, what degree of equipment engineering is acceptable?

Most instances promote all innovative technical developments within the rules. This largely contributes to new world records. Furthermore, it attracts interest from industrials sometimes, but not always, motivated by possible commercial outcomes. So, this is a vector of progress in the sport.

Other instances have chosen the standardization of equipment, applying the "same-for-all" principle. For instance, World Swimming Federation (FINA) has banned hi-tech swimsuits which cut down on fatigue and give swimmers more buoyancy and speed. The development and implementation of a universal throwing frame is currently examined. In principle, this position limits technical developments while potentially increasing access and participation.

To the best of my knowledge, international regulating bodies, such as the IPC, have yet to find a consensus around standardization. In the meantime, it is critical to continue to provide solid evidence of the real biomechanical benefits of this equipment to enlighten the debate.

SC*: Obviously, the debate around the standardization depends partially on technical progresses (e.g., new materials) but what about the medical progresses?*

LF: You are absolutely right. The ambiguity between sport equipment and assistive device generates another set of issues. How governing bodies of Paralympic sports are going to accommodate new medical discoveries leading to significant biomechanical advantages?

Let's take the example of sprinters with lower limb amputation. Typically, they wear their running prosthesis through a socket. Some amputees are already attaching their prosthesis through an osseointegrated fixation for activities of daily living [42-48]. In this case, the socket is replaced by an implant directly inserted into the bone of the residuum. Future generations of fixation are more likely to accommodate loading during sprinting. Athletes fitted with a fixation will have a tremendous advantage. For example, they will be able to train more since there will be no more friction between the skin of the residuum and the socket that causes blisters. Should athletes fitted with a socket and osseointegrated fixation belong to the same class?

Mechanical structures, such as leg exoskeletons, designed to transfer the load directly to the ground have been used by soldiers and firefighters as well as individuals with limited lower limb functions. This equipment could assist stationary throwers with cerebral palsy or spinal cord injuries to transit from the seating to the standing position. Should it be allowed?

Finally, recent developments in EMG are revolutionizing the activation of muscles or prosthesis fitted microprocessor-controlled artificial knees [45, 49]. Internal wires activating lower limb muscles of stationary throwers with spinal cord injury could facilitate balance. How functional outcomes of these athletes should be assessed during their classification?

SC*: Finally, the inclusion of Paralympians into able-bodied events is a *hot topic* of debate with many for and against. Considering an equal playing field what are your thoughts on this?*

LF: I have been fascinated by the debate around the participation of Oscar Pistorius in able-bodied running events. I have seen him running from the side of the track in a number of occasions: he is an impressive athlete!

Several scientific studies contributed to the controversy over whether he is at an unfair advantage competing against other sprinters, given that he compensates the absence of both legs below the knee by carbon-fiber prostheses [14, 21, 41, 50-57]. Some confirmed an unfair advantage. Others concluded to the equitable participation. All based on data presenting the typical intrinsic limits of any biomechanical performance analyses.

One of the most significant outcomes of this controversy is to raise the awareness of Pistorius' actual abilities. Indeed, I am astonished by the shift in perception. He is not seen as a "dis-abled" but as a "too-abled" athletes with a possible unfair advantage over able-bodied athletes! However, I will argue that whether his prostheses constitute an advantage or a disadvantage is irrelevant. In my view, a competitive event aims at discriminating the best athletes amongst a group of athletes with very similar initial biomechanical predispositions.

Consequently, I am ambivalent about inclusion of Paralympians into able-bodied events. I think inclusion and separation are both equally acceptable depending on the intent of the event. Athletic meetings on professional circuit seem to be a relevant platform for mixt events. Organizers can adapt the rules to make sure that the audience is captivated by the sporting and entertainment value of the competition. I think it is a great opportunity to showcase Paralympians' athletic abilities. However, I think official international event such as World Championships, Olympic and Paralympic Games should involve athletes under the premises of the classification regrouping as fairly as possible individuals with similar biomechanical predispositions.

The alternation of events involving abled-bodied and athletes with a disability within the competition is far more interesting and respectful. Indeed, the Olympic Games have hosted wheelchair sprinting events as demonstration. A full integration of both Olympic and Paralympic Games presents significant logistical challenges (e.g., duration of the Games, size of the Olympic Village). However, such arrangement might equally acknowledge and value the performance of all athletes regardless of their functional outcomes.

References

1. Vanlandewijck YC. Sporty science in the Paralympic movement. *Journal of Rehabilitation Research and Development* 2006; 43: 12-20.
2. Parasport. Self-assessment wizard. 2012 [cited 2012 8/05/2012]. Available from: http://www.parasport.org.uk/decision.asp?section=101&sectionTitle=Self+assessment+Wizard. Acccessed 31/05/2012.
3. O'Riordan A, Frossard L. Seated shot-put – What's it all about? *Modern Athlete and Coach* 2006; 44: 2-8.
4. Frossard LA, O'Riordan A, Goodman S. Applied biomechanics for evidence-based training of Australian elite seated throwers, in Sport for persons with a disability, ICSSPE, Editor 2006; *International Council of Sport Science and Physical Education "Perspectives" series*; 175-198.
5. Higgs C, Babstock P, Buck J, Parsons C, Brewer J. Wheelchair classification for track and field events: A performance approach. A*dapted Physical Activity Quarterly*; 1990 7: 22-40.
6. McCann BC. The medical disability-specific classification system in sports. In Vista '93 The Outlook: P*roceedings of the International Conference on High Performance Sport for Athletes with Disabilities*. 1993; Edmonton.
7. Williamson DC. Principles of classification in competitive sport for participants with disabilities: A proposal. *Palaestra* 1997; 13: 44-48.
8. Laveborn M. W*heelchair Sports: International Stoke Mandeville Wheelchair Sports Federation: ISMWSF track & field classification handbook*. 2000, Aylesbury, UK.
9. Tweedy SM. Taxonomic theory and the ICF: Foundation for the Unified Disability Athletics Classification. *Adapted Physical Activity Quarterly* 2002 19: 221-237.
10. Chow JW, Mindock LA. Discus throwing performances and medical classification of wheelchair athletes. *Medicine & Science in Sports & Exercise* 1999; 99: 1272-1279.
11. Vanlandewijck YC, Chappel RJ. Integration and classification issues in competitive sports for athletes with disabilities. *Sport Science Review* 1996; 5: 65-88.
12. Beckman EM, Tweedy SM. Towards evidence-based classification in Paralympic athletics: evaluating the validity of activity limitation tests for use in classification of Paralympic running events. *British Journal of Sports Medicine* 2009; 43: 1067-1072.
13. Frossard L, O'Riordan A, Goodman A (eds). *Performance analysis of stationary throwers: data for evidence-based classification* (First edition). http://eprints.qut.edu.au/18099/1/c18099.pdf2009, Queensland University of Technology.
14. van Hilvoorde I, Landeweerd L. Disability or extraordinary talent—Francesco Lentini (Three Legs) Versus Oscar Pistorius (No Legs). *Sport, Ethics and Philosophy* 2008; 2: 97-111.
15. Tweedy SM, Vanlandewijck YC. International Paralympic Committee position stand—background and scientific principles of classification in Paralympic sport. *British Journal of Sports Medicine* 2011; 45: 259-269.

16. Keogh JWL. Paralympic sport: an emerging area for research and consultancy in sports biomechanics. *Sports Biomechanics* 2011; 10: 234-253.
17. Derman W, Ferreira S, Subban K,Richard de Villiers R. Transcendence of musculoskeletal injury in athletes with disability during major competition. *SAJSM* 2011; 23: 95-97.
18. Ferrara, M. and W.E. Buckley, Athletes with disabilities injury registry. *Adapted Physical Activity Quartely* 1996; 13: 50-60.
19. Ferrara MS, Buckley WE, McCann BC, Limbird TJ, Powell JW, Robl R. The injury experience of the competitive athlete with a disability: prevention implications. *Med Sci Sports Exerc* 1992; 24: 184-188.
20. Ferrara MS, Peterson CL. Injuries to athletes with disabilities: Identifying injury patterns. *Sports Medicine* 2000; 30: 137-143.
21. Jones C, Wilson C. Defining advantage and athletic performance: The case of Oscar Pistorius. European *Journal of Sport Science* 2009; 9: 125-131.
22. Ramirez M, Yang J, Bourque L, Javien J, Kashani S, Limbos MA, Peek-Asa C. Sports Injuries to High School Athletes With Disabilities. *Pediatrics* 2009; 123: 690-696.
23. Frossard L, Smeathers J, O'Riordan A, Evans J, Goodman S. Quality control procedure for kinematic analysis of elite seated shot-putters during world-class events. *The Sport Journal* 2008; 11 (1): 1. (http://www.thesportjournal.org/article/quality-control-procedure-kinematic-analysis-elite-seated-shot-putters-during-world-class-ev): Accessed 01/06/2012.
24. O'Riordan A, Goodman S, Frossard L. Relationship between the parameters describing the feet position and the performance of elite seated discus throwers in Class F33/34 participating in the 2002 IPC World Championships. In *AAESS Exercise and Sports Science Conference*. 2004.
25. Frossard L, O'Riordan A, Goodman S, Smeathers J. Video recording of seated shot-putters during world-class events. 3rd International Days on Sports Science. In *3rd International Days on Sports Science*; 2005.
26. Frossard L, Stolp S, Andrews M. Video recording of elite seated shot putters during world-class events. *The Sport Journal* 2006; 9: **http://www.thesportjournal.org/2006Journal/Vol9-No3/Frossard.asp**. Accessed 01/06/2012.
27. Frossard L, O'Riordan A, Goodman S. Throwing frame and performance of elite male seated shot-putters. *Sports Technology* 2010; 3: 88-101.
28. Frossard L, Smeathers J, O'Riordan A, Goodman S. Initial parameters of the shot's trajectory of male and female gold medallists seated shot-putters during world-class events. *Adapted Physical Activity Quarterly* 2007; 24: 317-331.
29. Chow JW, Chae W, Crawford MJ. Kinematic analysis of shot-putting performed by wheelchair athletes of different medical classes. *Journal of Sports Sciences* 2000; 18: 321-330.
30. Bartonietz K, Borgström A. The throwing events at the World Championships in Ahtletics 1995, Göteborg: Technique of the world's best athletes. Part 1: Shot put and hammer throw. *New Studies in Athletics* 1995; 10: 43-63.
31. Čoh M, Štuhec S, Supej M. Comparative biomechanical analysis of the rotational shot put technique. *Collegium Antropologicum* 2008; 32: 249-256.
32. Dessureault J. Kinetic and kinematic factors involved in shotputting. *Biomechanics* 1978; 6B: 51-60.
33. Lichtenburg DB, Wills JG. Maxmizing the range of the shot put. *American Journal of Physics* 1978; 46: 546-549.
34. Linthome N. Optimum release angle in the shotput. *Journal of Sports Sciences* 2001; 19: 359-372.
35. Luhtanen P, Bloqvist M, Vänttinen T. A comparison of two elite shot putters using the rotational shot put technique. *New Studies in Athletics* 1997; 12: 25-33.

36. McCoy, R.W., R.J. Gregor, W.C. Whiting, and R.G. Rich, Technique analysis: Kinematic analysis of elite shot-putters. Track Technique, 1984: p. 2868-2871.
37. Pagani T. Technique analysis: Mechanics and technique of the shot. *Track Technique* 1981; 2601-2602.
38. Sušanka P, Štepánek J. Biomechanical analysis of the shot put. In S*cientific Report on the Second IAAF World Championship* 1988; IAAF Monarco: 1-77.
39. Tsirakos DM, Bartlett RM, Kollias IA. A comparative study of the release and temporal characteristics of shot put. *Journal of Human Movement Studies* 1995; 28: 227-242.
40. Zatsiorsky VM, Lanka GE, Shalmanov AA. Biomechanical analysis of shotputting technique. *Exercise and Sports Science Reviews* 1981; 9: 353-387.
41. Fuss, F.K., Closing the gap through technology. Sports Technology, 2008. 1(4-5): p. 169-171.
42. Frossard L, Hagberg K, Haggstrom E, Lee D, Gow DL, Branemark R, Pearcy M. Functional outcome of transfemoral amputees fitted with an osseointegrated fixation: Temporal gait characteristics. *Journal of Prosthetics and Orthotics Interntaional* 2010; 22: 11-20.
43. Frossard L, Stevenson N, Smeathers J, Lee D, Gow DL, Gray S, Sullivan J, Daniel C, Häggström E, Hagberg K, Brånemark R. Daily activities of a transfemoral amputee fitted with osseointegrated fixation: continuous recording of the loading for an evidence-based practice. *Kinesitherapie Revue* 2006; 6: 53-62.
44. Frossard L, N. Stevenson, J. Sullivan, M. Uden, and M. Pearcy, Categorization of activities of daily living of lower limb amputees during short-term use of a portable kinetic recording system: A preliminary study. *Journal of Prosthetics and Orthotics International* 2011; 23: 2-11.
45. Kuiken T. Targeted Reinnervation: Development of neural interfacef for artificial limbs. In III *International conference Advances in Orthopaedic Osseointegration* 2010; Gothenburg, Sweden: Universiy of California, San Francisco School of Medicine.
46. Lee W, Frossard L, Hagberg K, Haggstrom E, Brånemark R. Kinetics analysis of transfemoral amputees fitted with osseointegrated fixation performing common activities of daily living. *Clinical Biomechanics* 2007; 22: 665-673.
47. Lee WC, Frossard L, Hagberg K, Haggstrom E, Gow DL, Gray S, Branemark R. Magnitude and variability of loading on the osseointegrated implant of transfemoral amputees during walking. *Medical Engineering & Physics* 2008; 30: 825-833.
48. Pitkin, M., On the way to total integration of prosthetic pylon with residuum. *Journal of Rehabilitation Research & Development* 2009; 46: 345-360.
49. Pitkin M, Cassidy C, Muppavarapu R, Edell D. Recording of electric signal passage trough a pylon in direct skeletal attachment of leg prostheses. *IEEE Transaction and Biomedical Engineering;* 2012. In press.
50. Chockalingam N, Thomas NB, Smith A, DunningD. By designing 'blades' for Oscar Pistorius are prosthetists creating an unfair advantage for Pistorius and an uneven playing field? P*rosthetics and Orthotics International* 2011; 35: 482-483.
51. Burkett B, McNamee M, Potthast W. Shifting boundaries in sports technology and disability: equal rights or unfair advantage in the case of Oscar Pistorius? *Disability & Society* 2011; 26: 643-654.
52. McNamee M. After Pistorius: Paralympic Philosophy and Ethics. *Sport, Ethics and Philosophy* 2011; 5: 359-361.
53. Norman ME, Moola F. 'Bladerunner or boundary runner'?: Oscar Pistorius, cyborg transgressions and strategies of containment. *Sport in Society* 2011; 14: 1265-1279.
54. Swartz L, WatermeyerB. Cyborg anxiety: Oscar Pistorius and the boundaries of what it means to be human. *Disability & Society*; 2008; 23: 187-190.
55. Edwards SD. Should Oscar Pistorius be Excluded from the 2008 Olympic Games? *Sport, Ethics and Philosophy;* 2002 2: 112-125.

56. Wolbring G. Paralympians Outperforming Olympians: An Increasing Challenge for Olympism and the Paralympic and Olympic Movement. *Sport, Ethics and Philosophy;* 2012. 6: 251-266.
57. Lechler K, Lilja M. Lower extremity leg amputation: An advantage in running? *Sports Technology* 2008; 1(4-5): 229-234.