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What gaps exist in biomechanics and motor control research in Paralympic sports? A scoping review focussed on performance and injury risk

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ABSTRACT
In Paralympic sport, athletes, coaches and administrators seek medal-winning outcomes. Research in the fields of biomechanics and motor control can support the quantification of performance measures and injury risk. The aim of this article is to review the state of existing research and identify gaps offering researchers and practitioners targeted paths for creating competitive advantages. This review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analysis extension for Scoping Reviews (PRISMA-ScR). Four electronic databases were searched in accordance with selected terms and inclusion/exclusion criteria. A custom data charting matrix was used to identify relevant characteristics. From the 3363 retrieved articles, 237 studies covering 24 Paralympic sports were included. A new metric, medal events per included study (MEPIS), was developed. Research gaps were identified in the sports studied, impairment types, gender balance, the injury reduction process, and the application of motor control research, leading to suggested directions targeting Paralympic success.

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Introduction

The Olympic motto “Faster, Higher, Stronger” applies equally to athletes with a disability (AD) as for non-disabled athletes (ND). The Paralympic Games has grown rapidly from eight sports with 400 participants in Rome 1960 (International Paralympic Committee, 2021b) to 22 sports with 4393 participants in Tokyo 2020 (International Paralympic Committee, 2021c). The Paralympic Winter Games has also expanded rapidly from two sports with 198 participants at its inception in 1976 (International Paralympic Committee, 2022a) to six sports with 15 disciplines involving 2897 participants in 2022 (International Olympic Committee, 2022). However, whether this growth in participation has been matched by increases in research requires investigation. Research is one of the nine pillars of sports policy factors leading to sporting success (De Bosscher et al., 2006), and one of four key strategies adopted by the United Kingdom Government prior to that nation’s success at the 2012 London Olympic Games (Houlihan & Green, 2009). However, in Paralympic sport it is not clear if there is a correlation between countries in which research is performed and subsequent medal success (Legg et al., 2011). A gold medal can reward not only the individual athlete but also the sport, since countries tend to invest more in those sports that have provided medal success (De Bosscher et al., 2019). This interplay between investment and achievement highlights the critical role of research and technological advancement in sport.

Sports biomechanists have two seemingly conflicting aims: to improve sports performance and to reduce injury risk (Bartlett & Bussey, 2012). These aims can appear contradictory because the methods used to enhance performance, such as altering movement mechanics, can sometimes elevate the risk of injury. Conversely, strategies focused on minimising injury, such as focusing on safer techniques, might limit performance improvements. Balancing these dual objectives requires a nuanced approach to ensure athletes can achieve peak performance while maintaining their health and longevity in the sport. In the performance domain, developments in high-tech prostheses have enabled Paralympians to achieve levels of performance approaching Olympic levels (Burkett, 2010). An example of this performance improvement is highlighted in a review by Fletcher et al. (2021), where the F44 long jump gap between the Paralympic champion and the Olympic champion has reduced steadily from 35% in 1992 to 2% in 2016. Other examples of how biomechanics research has enabled elite athletes better interact with their environment and develop enhanced movement techniques are in swimming suits, running shoes and javelins (Li, 2012) and Para Canoe, where custom made lower-limb prosthesis improved propulsion impulse (Rebensburg et al., 2019).

The path to improved performance is often through substantially increased training load (Foster, 1998) and specificity, but rapid loading changes on the body are likely responsible for many soft-tissue injuries (Gabbett, 2016).

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Paralympic athletes often face additional challenges resulting from their impairments (Weiler et al., 2016), represented in Paralympic sports as spinal cord injury, limb deficiency, vision impairment, intellectual impairment and other neurological and musculoskeletal disorders (International Paralympic Committee, 2021a). Paralympic winter sport athletes are twice as likely to suffer an injury than Olympic athletes at their respective games, with their impairments and adapted equipment often contributing to those injuries (Fagher et al., 2022). The consequences of injury to AD can be more debilitating than for ND (Webborn et al., 2006) with the most common injury incurred at the 2012 Paralympic Games being shoulder injuries and, of those, chronic overuse injuries were prevalent amongst wheelchair athletes (Willick et al., 2013). Such injuries may impact the AD's ability to self-ambulate and, therefore, injury risk prevention and mitigation is crucial to maintaining an AD's quality of life.

Whereas biomechanics can quantify the elements of sporting movements (Farana et al., 2021), motor control is the ability to execute those movements with balance and control in the presence of perturbations, both expected and unexpected (Winter et al., 1990). Sporting movements by AD are subject to additional constraints imposed by individual impairments which may lead to revised patterns of co-ordination and self-organisation (Keogh, 2011; Newell, 1986). Performance improvements result from motor learning. Previous motor learning research has been primarily laboratory-based and the application to complex sport-based skills in limited (Shea & Paull, 1996). Furthermore, Gabbett and Masters (2011) noted that much of the evidence is from studies of novice performers rather than those of the elite. Specifically, the rate of motor learning in elite and sub-elite athletes has been shown to predict competition rankings in later years (DiCagno et al., 2014).

These two areas of biomechanics and motor control play a critical role in performance and injury. However, despite the importance of injury risk reduction, to the authors' knowledge, no prior reviews of Paralympic sport (Fletcher et al., 2021; Morrien et al., 2017) have reported on injury biomechanics research. Nor are we aware of reviews considering summer and winter sports, and these gaps support the urgent need for a review with a broad scope. Therefore, the aim of this study is to provide a review of literature across all Paralympic sports, both summer and winter, considering biomechanics and motor control influences on performance and injury risk. It will highlight gaps and opportunities for future work to help create successful outcomes for athletes, coaches, and sporting organisations at the Paralympic level.

Method

This scoping review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analysis extension for Scoping Reviews (PRISMA-ScR) guidelines (Tricco et al., 2018). The protocol for this review was registered prospectively with a protocol registry organisation in February 2022.

Criteria for study inclusion

Studies were included if they complied with the following criteria:

Study design

The following study types were included: randomised control trials, non-randomised trials, case studies, case control studies and randomised experimental studies. Opinion pieces, commentaries, and all types of reviews were excluded.

Inclusions/Exclusion criteria

All participants were at least Paralympic level athletes competing in Paralympic summer or winter sports as listed by the IPC (International Paralympic Committee, 2022b). Studies including a control group of ND athletes were included. Studies were to target the analysis of performance or injury risk in the areas of biomechanics or motor control, be written in English language, be peer-reviewed and published with full-text available. Studies that were primarily performed to provide evidence for Paralympic classification were excluded. All studies must yield quantitative data representative of Paralympic sporting movements either by a stand-alone study or by retrospective broadcast analyses of Paralympic competition. There were no date limits set for inclusion.

Information sources

An electronic database search was performed using Scopus, PubMed, SPORTDiscus and Google Scholar databases, initially on 28 June 2021, and updated on 26 June 2023.

Search strategy

The search terms used were: Paralympi* OR disabled athlete OR para-sport OR parasport OR para sport OR elite para* OR athlete with a disability OR athlete with disability OR wheelchair athlete AND motor control OR motor learning OR motor skill OR skill acquisition OR dynamic system* OR dynamical system* OR biomechanic* OR kinematic analys* AND performance OR injury.

Screening

Search results were uploaded to EndNote 20 ver.20.0.1 (Clarivate, Philadelphia, PA) and duplicates removed. They were then exported to Covidence (Veritas Health Innovation, Melbourne, AU) for screening. Titles and abstracts from the search outcome were screened for relevance by the lead author alone. Full texts were then screened independently by the lead author (RL) and a second reviewer (LW). Any conflicts were resolved by mutual discussion. In cases of unresolved conflict, a third reviewer would act as an adjudicator. Full-text screening agreement between reviewers was assessed in Covidence via Cohen's kappa statistic with the following gradings: ≤0 no agreement, 0.01–0.20 none to slight, 0.21–0.4 fair,

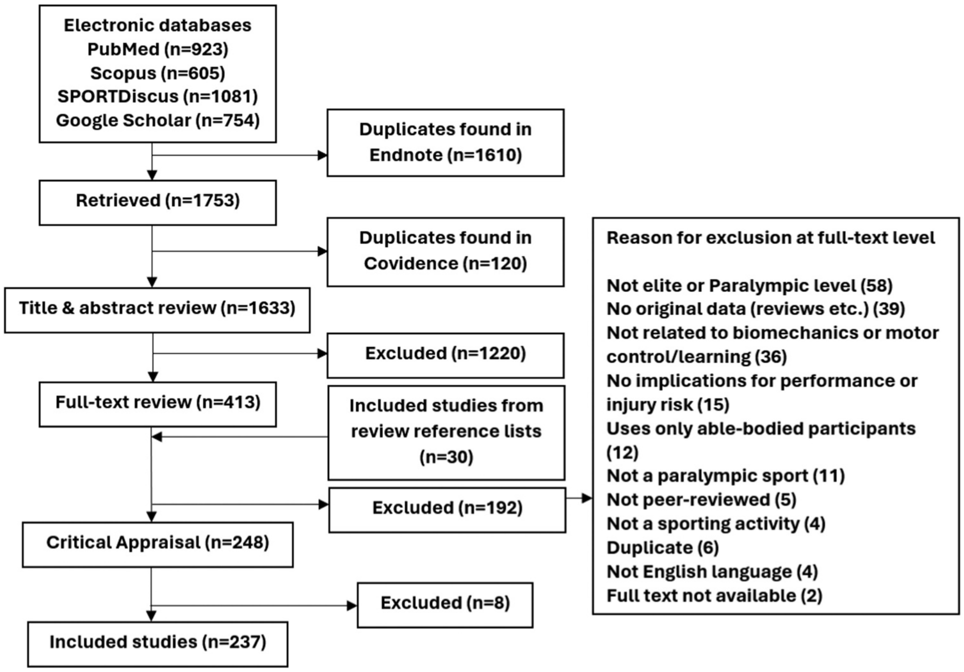

Figure 1. PRISMA flowchart of search results.

0.41–0.60 moderate, 0.61–0.80 substantial, 0.81–1.00 almost perfect agreement (McHugh, 2012). To assist in literature saturation, the references contained within any review papers excluded at full-text screening were scrutinised with relevant, non-duplicate prior studies added to the final included studies list. An overview of the search and screening process is illustrated in Figure 1.

Data charting process

Data from eligible studies were charted using a custom spreadsheet using Microsoft Excel (Microsoft Corporation, WA, USA). Data extracted performed by RL and LW included: Country of origin, source of funding, sport contested, type of research (biomechanics or motor control), domain of investigation (performance or injury risk), characteristics of the case participants (gender, Paralympic classification, impairment type), study design and metrics analysed. The completed data chart is shown in supplementary materials (Table S1).

Critical appraisal of individual sources

Although appraisal of individual studies is optional for scoping reviews, this review aims to avert the risk of potential gaps being papered over by studies of poor quality. This review addresses seven key questions based on screening, methodology and ethics as per Table 1 (Munn et al., 2018; Tricco et al., 2018). Two independent reviewers appraised each study and assigned a yes (2 points), no (0 points) or unclear (1 point) response to each question. A total score of less than eight would lead to the exclusion of the study. The completed appraisal is shown in supplementary materials (Table S2).

Table 1. Critical appraisal questions.

Reference	Questions
S1	Is/are there clear research question(s)?
S2	Does the collected data allow the addressing of the aims/objectives of the study?
M1	Are the selected participants appropriate to address the aims/objectives of the study?
M2	Are the methods of testing, data analysis and statistical analysis clearly detailed?
E1	Is there a statement pertaining to conflict of interest?
E2	Was the study reviewed and approved by the relevant ethics committee/institutional review board?
E3	Was informed consent obtained?

Synthesis of results

The studies were grouped by research type (biomechanics or motor control) and domain (performance or injury risk), with further groupings created for motor tasks based on similarities of movements and primary variables.

Gap identification

Of the seven types of research gaps identified in the theoretical model proposed by Miles (2017), this scoping review utilised the collected and synthesised data to identify two main types. Empirical and population gaps are primarily represented by a high value of the medal events per included study (MEPIS) metric. This new metric is proposed to identify sports, or other characteristics, for which there are a relatively high number of mean collective medals awarded for a given sport with different subevents but are under-represented in current research. Furthermore, future research opportunities that were identified within studies but have not yet been addressed, also represent gaps.

Results

Selection of sources of evidence

Database searches identified 1753 records with duplicates removed 1633 studies were excluded at title and abstract screening plus a further 192 following full text screening. A review of the reference lists of excluded review papers yielded 30 additional studies not captured in the electronic searches. A total of 237 studies were included for the analysis. Inter-rater reliability of full-text screening was substantial between reviewers (kappa = 0.620). Subsequent critical appraisal excluded a further eight studies, leaving a total of 237. A list of references for all included studies is shown in supplementary materials (Item S3).

Critical appraisal of studies following full-text screening

A mean critical appraisal rating of 11.9 out of 14 was obtained for all studies. A conflicts of interest statement (question E1) was included in only 47.5% of total studies, although this score improved to 69.7% for those studies published in 2018 or later. Institutional ethics review board approval (question E2) was documented in 73.8% of studies. Informed consent (question E3). was documented in 79.2% of studies. Question M2 posed the question of whether the method, data analysis and statistical analysis was clear, allowing replication of the study, and for which 84.6% of studies were in compliance. Questions M1, S1 and S2 as detailed in Table 1 received full marks for more than 99% of studies. A total of eight studies were excluded following the critical appraisal, based on a total score of less than eight.

Characteristics of sources of evidence

The number of included studies based on the year of publication has increased markedly since 1988, reaching a peak in 2021 as shown in Figure 2. Amongst the included studies, 31 countries of origin were represented, with Great Britain being the most prolific having 30 included studies, followed by the United States (24), Brazil and Australia (23 each) and Japan (15). The country of origin was assigned based on the following criteria, in order: 1) country of funding source, and 2) country of the lead author's institution. Included studies amongst the 10 most prolific countries of origin represent 80.1% of the total studies. External funding was acknowledged in 32.5% of the included studies.

There were 186 case studies (~78%), 30 competition analyses, six studies addressing modelling, five studies of measurement devices, eight prospective cohort studies and three retrospective cohort studies. Of the included studies, 81 offered a hypothesis, and 42 studied an intervention (30 acute and 12 longitudinal). Two hundred and twelve studies focused on performance with the remaining 24 considered injury risk. Twenty-five studies considered the impact of motor control on sporting movements, whilst 211 examined the biomechanics of motor tasks.

There is a premise underlying the research question that scientific research, particularly in areas such as biomechanics and motor control, contributes to enhanced athletic performance and success (De Bosscher et al., 2016). To explore this relationship, Figures 3 and 4 plot the countries conducting such research against their medal counts at the most recent Summer and Winter Paralympic Games. While these figures provide a global overview, it is important to acknowledge that research output is only one of several critical factors influencing Paralympic success. Investment in training facilities, coaching development, competition structures, and broader socioeconomic determinants also play significant roles, as highlighted by De Bosscher et al. (2016), Buts et al. (2013), and Pankowiak et al. (2023). This analysis aims to provide a more nuanced understanding of how research, alongside these other factors, contributes to Paralympic performance.

Sports

Table 2 shows the number of events for each sport, supplemented to show the number of included studies for each sport and the corresponding value of MEPIS.

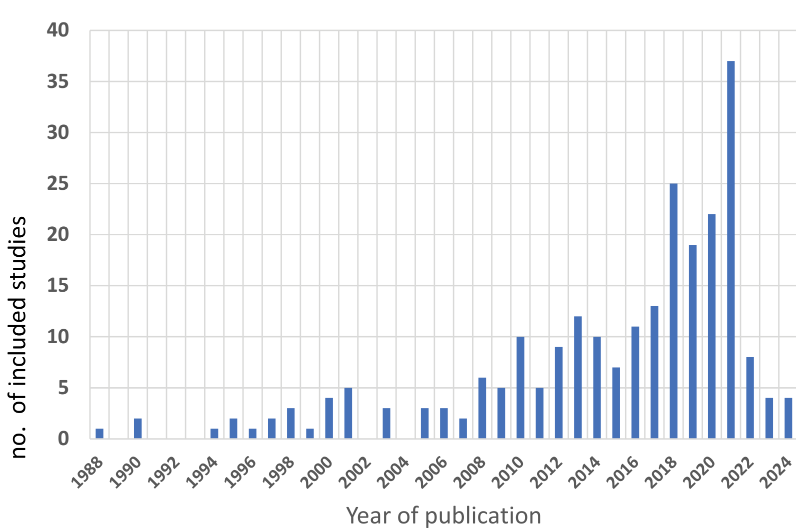

Figure 2. Total number of included biomechanics and motor control studies in Paralympic sport based on year of publication.

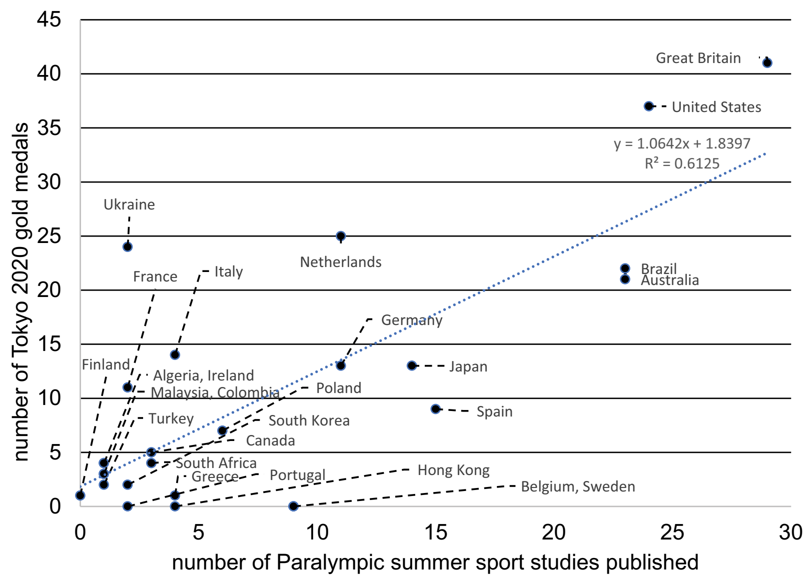

Figure 3. Summer sport studies versus Tokyo 2020 gold medals.

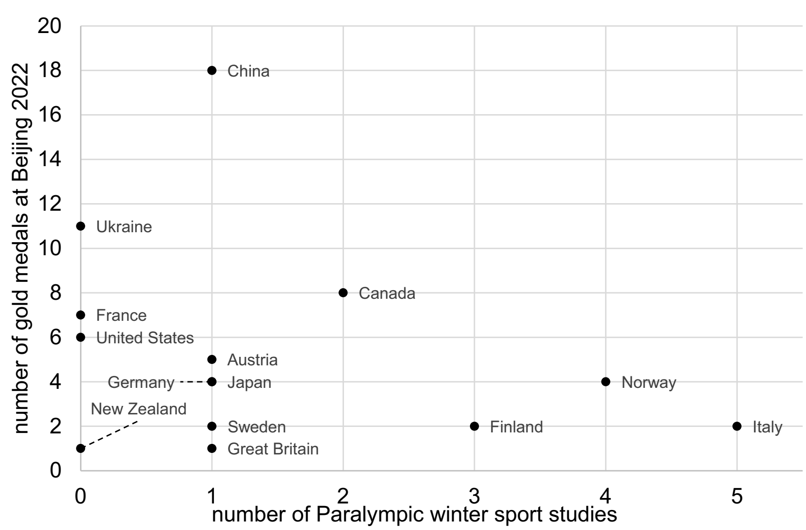

Figure 4. Winter sport studies versus Beijing 2022 gold medal.

Participants

There were 10,923 participants (AD) represented in the studies with 7100 nominated as male, 3205 female and 618 where gender was not nominated, and for which clarification sought from authors was not provided. The median number of participants was 11. Female participants comprised 31.1% of the total where gender was nominated, whereas medal events for female athletes comprise 47.5% of the total at Tokyo 2020 and Beijing 2022 (inclusive of mixed gender events).

Impairment types

There are 10 eligible impairments included by the IPC (IPC, 2021a). Eight of them are classified as physical, whilst the others are vision impairment (VI), and intellectual impairment (II). 18 studies included VI participants, whilst 4 included II participants. There are three sports solely for athletes with VI; (Goalball, Para Judo and Football (5-a-side)), whilst another six include medal events for VI athletes. In total, there are 99 medal events for VI athletes, and 20 medal events for athletes with II.

There were 142 studies where at least one participant used an adaptive technology device (AT), for example: wheelchair, prosthetic limb, brace or orthotic, throwing chair, sit-ski or sledge.

Motor tasks

Motor tasks were classified across sport boundaries to synthesise sporting movements with common studied variables, e.g., wheelchair propulsion for Wheelchair Rugby, Wheelchair Basketball and Para Athletics. Water propulsion covered swimming, Para Canoe and Para Rowing. Poling propulsion covered winter sports using

Table 2. Medal events at Tokyo 2020/Beijing 2022 and included studies by sport.

Sport	# of medal events: Male	Female	Mixed	Total	# of included. studies	MEPIS
Para Equestrian	0	0	11	11	0	
Para Taekwondo	3	3	0	6	0	
Para Biathlon	9	9	1	19	0	
Para Snowboard	6	2	0	8	0	
Para Badminton	7	7	2	16	1	16.0
Shooting Para Sport	3	3	7	13	1	13.0
Para Table Tennis	17	14	0	31	3	10.3
Para Archery	3	3	3	9	1	9.0
Para Triathlon	4	4	0	8	1	8.0
Para Cross Country Skiing	9	9	1	19	3	6.3
Para Swimming	76	67	3	146	30	4.9
Para Judo	7	6	0	13	3	4.3
Para Alpine Skiing	15	15	0	30	7	4.3
Para Cycling	29	20	2	51	14	3.6
Wheelchair Fencing	8	8	0	16	6	2.6
Para Athletics	93	73	1	167	70	2.4
Para Powerlifting	10	10	0	20	12	1.7
Boccia	0	0	7	7	4	1.7
Para Canoe	5	4	0	9	6	1.5
Wheelchair Tennis	2	2	2	6	6	1.0
Para Rowing	1	1	2	4	4	1.0
Goalball	1	1	0	2	4	0.5
Sitting Volleyball	1	1	0	2	4	0.5
Wheelchair Curling	0	0	1	1	3	0.3
Football 5-a-side	1	0	0	1	3	0.3
Para Ice Hockey	0	0	1	1	4	0.3
Wheelchair Basketball	1	1	0	2	18	0.1
Wheelchair Rugby	0	0	1	1	18	0.05

MEPIS=medal events per included study, #=number.

poles to aid propulsion in both sitting and standing configurations. Explosive object manipulation included throwing sports. Fine control object manipulation included Boccia, Wheelchair Curling, Para Table Tennis, Para Badminton, Para Archery and Wheelchair Fencing. Some sports may have more than one primary motor task, e.g: wheelchair propulsion and fine control object manipulation for Wheelchair Basketball. In these cases, the study was classified by the motor task representing the primary variable within the individual study. Within Table 3, only those motor tasks which cross sporting boundaries or are subsets of a sport appear.

Table 3. MEPIS for various characteristics.

Characteristic	# of medal events	# of included studies	MEPIS
Athletes with VI	99	18	5.5
Athletes with II	20	4	5.0
MT – Water propulsion	159	33	4.81
MT – Explosive object manipulation	57	14	4.07
MT – Fine control object manipulation	97	25	3.88
Female athletes	306[a]	109[b]	2.80
Male athletes	355[a]	205[b]	1.73
Summer sports	541	223	2.32
Winter sports	78	33	2.36
MT – Running	67	27	2.48
MT – Jumping	20	13	1.54
MT – Poling propulsion	23	15	1.53
MT – Wheelchair propulsion	30	62	0.48

a = includes mixed gender events; b = where gender is nominated, MEPIS= medal events per included study, VI = vision impairment, II = intellectual impairment, MT = motor task, # = number.

Table 4. Characteristics in injury-related studies.

Van Mechelen's "Sequence of prevention"[a]	# of case studies	# of RCS	# of PCS	Total # of studies
Total	10	5	9	24
1. Incidence & severity	5	5	9	19
2a. Aetiology & mechanism	7	0	1	8
2b. Future research in step 2?	5	2	7	13
3a. Preventive measures	6	1	0	7
3b. Future research in step 3?	4	0	4	8
4. Implementation effectiveness	0	0	2	2

a – from van Mechelin et al. (1992), RCS = retrospective cohort study, PCS = prospective cohort study, # = number.

Injury risk

Of the 24 studies concerned with injury risk, there were 14 studies on individual sports with wheelchair court sports being the most prevalent ($n = 8$). Ten studies covered multi-sports with seven of them being longitudinal studies of duration greater than six months. A chart showing the study types can be seen in Table 4.

In considering the 4-step prevention process of van Mechelin et al. (1992, p. 19) studies reported incidence & severity of injuries (Step 1), eight reported possible aetiology and mechanisms of injury (Step 2) whilst 13 suggested that it be worthy of future research. Seven studies suggested possible preventive actions (Step 3) (including 3 studies concluding that sport practice reduces incidence of injury), whilst eight suggested that prevention be a subject of future research. Only two studies reported the effectiveness of preventive actions (Step 4), those being extrinsic risk factors addressed by the IPC at the Sochi 2014 and PyeongChang 2018 Paralympic Winter Games in the sport of Para Alpine Skiing.

Motor control research

Of the 25 studies concerned with motor control, there were 14 individual sports represented, covering 7 motor tasks, with fine control object manipulation being covered by the most studies ($n = 13$) (Table 5).

Discussion

The aim of this review was to provide a map of the evidence across all Paralympic disciplines, both summer and winter, considering biomechanics and motor control influences on performance and injury risk. This review found a trend suggesting that biomechanics and motor control research in Paralympic sports is an emergent theme with 69% of all the Paralympic sports studies published within the past decade and an expectation that studies published in the second half of 2022 will continue the current trajectory. However, during the updated search this review found that research output dropped during 2022–2024, this maybe due to the effects of COVID-19 impacting research projects.

A general trend indicated that countries of origin publishing more studies have a greater share of gold medals won in Tokyo 2020. However, it should be noted that several countries well-represented in the medal tally, including China, Russia and Ukraine have no, or very few, included studies published, most likely because of the non-English language exclusion criteria. There is no trend evident in the Beijing 2022 data, possibly due to the low number of included studies from winter sports.

As medal success is one of the key performance indicators for Olympic and Paralympic sports organisations (De Bosscher et al., 2008; Madella et al., 2005; Sam, 2012), then research should likely be attracted to where the most medals are available. Results of this review show that this has not necessarily been the case. Of the 28 Paralympic sports, the following four (with their Paralympic Games introduction date shown in parentheses) were not represented in the included studies; Para Equestrian (1996), Para Taekwondo (2020), Para Biathlon (1994) and Para Snowboard (2020). These sports represent gaps in the research, as all can benefit from biomechanics or motor control research to improve performance or reduce injury risk. For example, Para Equestrian comprises 11 events and has no included studies despite key parameters of riders without disabilities influence on the horse being: seated dynamic balance (Yang & Hsieh, 2014), trunk posture, joint range of motion, and the temporal relationship of the rider's pelvis and trunk motions relative to the movements of the horse (Hobbs et al., 2020). These key parameters can be readily measured in on-field settings and even a horse simulator and could be studied in Para-athletes, demonstrating a key gap area of biomechanics research.

A further five sports are relatively under-represented in the included studies (MEPIS score in parentheses) are: Para Badminton (16.0), Shooting Parasport (13.0), Para Table Tennis (10.3), Para Archery (9.0) and Para Triathlon (8.0) These nine sports represent empirical gaps as defined by Miles (2017) and present 77 gold medal opportunities.

The MEPIS metric reveals that female athletes have a MEPIS of 2.80, compared to 1.73 for males, indicating a significant under-representation of females in research studies (Miles, 2017). This disparity underscores a population gap where female athletes at not proportionally studied relative to their medal opportunities. Additionally, the representation of females within studies, currently at 31.1% further illustrates

Table 5. Characteristics of motor control studies.

Element of motor control	Motor task	Impairment/condition	# of studies
Sensory components	Balance	VI	2
		various	2
	Fine control object manipulation	various	4
	Jumping	VI	2
Reaction time	Fine control object manipulation	II	2
	Running	VI	1
Motor learning	Fine control object manipulation	various	2
Cognitive mediation		not defined	1
Practice conditions		CP	1
Augmented feedback	Water propulsion	VI	1
Motor learning		CP	1
Motor rhythmicity	Running	amputee	1
Muscle activation patterns	Fine control object manipulation	not defined	4
	Cycling	not defined	1

VI = visual impairment, II = intellectual impairment, CP = cerebral palsy.

this gap, which may widen with the International Paralympic Committee's ongoing efforts to equalise the number of events open to males and females (International Paralympic Committee, 2010). For instance, recent changes to Paris 2024 in Para Athletics indicate a net loss of three events for men, exacerbating the imbalance relative to women's events.

Of the seven motor tasks, sports categorised with fine motor control object manipulation such as Para Fencing, Para Table Tennis, Para Badminton or Para Archery have the highest MEPIS value of 5.7. This value, in most cases is exceeded by the MEPIS of the sport itself, so this area of motor task would not be considered a research gap per se. However, there may be useful information regarding the research outcomes that could be translated to other sports.

Adaptive technologies (AT) are widespread in Paralympic sports and may be either necessary (e.g., running and jumping for lower-limb amputees), prescribed within the sport (e.g., Para Ice Hockey, Sit-skiing), or optional (e.g., track cycling or alpine skiing for unilateral lower-limb amputees, athletics for unilateral upper-limb amputees). It is therefore not possible to assign a MEPIS value for the use of an AT, making it difficult to determine whether the use of, or absence of, an AT constitutes a research gap. Further exploration of this question by researchers and practitioners may prove beneficial.

The results of the included injury studies show shortcomings in the maturity of the injury prevention process in that very few of the studies address the aetiology and mechanism of injuries. Krosshaug et al. (2005) described a variety of research approaches to define mechanisms of injury including video and laboratory motion analyses. Kerin et al. (2022) used a systematic visual video analysis to define the mechanisms of acute hamstring injuries in professional rugby players using a collection of match and training videos over a 3-year period. There are shortcomings to video analysis, including not being able to capture every significant event with adequate quality of vision. A future possibility for mechanism of injury analysis is the use of wearable technology coupled with marker less Pose AI (machine learning) to calculate loadings on biological tissue as studied by Matijevich et al. (2020). However, validity and reliability of wearable technology coupling with marker less Pose AI is desperately needed, prior to application.

The authors are not aware of any detailed biomechanical analyses of injury mechanisms in Paralympic sport, despite it being a topic for future research identified in nine of the included studies. Risk factors for injuries in sport can be either extrinsic or intrinsic (Fagher & Lexell, 2014) with extrinsic factors such as regulation changes and protective equipment prescription already being proven effective in Paralympic sports of Para Alpine Skiing and Para Ice Hockey (Derman et al., 2019). Intrinsic factors such as neuromuscular training has proven successful in reducing injuries in football by means of the Federation Internationale de Football Association (FIFA) 11+ warm-up drill (Rossler et al., 2016). However, it should be noted that no studies involved musculoskeletal injury prediction models. Although a review by Bullock et al. (2022) found that models are poorly developed based on small sample sizes, have a high risk of bias with inappropriate evaluation process, and none of the models had been externally validated. Future development of these models would be beneficial to Para athletes given the impact the injury on their quality of life, for example, shoulder injuries for wheelchair athletes.

Some Paralympians have congenital impairments, while others experience impairments due to acute injury, often necessitating rapid skill acquisition within a shorter training period due to their low training age (Radtke & Ve Doll-Tepper, 2014). The ability to accelerate the motor learning process is particularly crucial in the Paralympic sports sphere, as the rate of motor learning is a valid predictor of future success (DiCagno et al., 2014). However, it is important to note that the onset of sport participation can vary widely among Paralympians, and there is no definitive evidence that those with congenital impairments necessarily start their sport earlier than those with acquired impairments. Four studies focused on motor learning with one of them investigating brain plasticity aiding motor learning. To maximise neuroplastic process, the use of virtual reality as a tool has been trialled (Levin et al., 2015) and this may be explored further to benefit Para athletes. Four studies covered muscle activation patterns with one noting that, for handcycling, experts have a greater mechanical efficiency due to the timing of agonist activation/deactivation (Kratzenstein & Brückner, 2021). This characteristic is applicable across all cyclic sporting movements and could be an opportunity for researchers in Paralympic sport. Notably, no studies looked at the role of movement variability to counter task and environment constraints to maximise performance or reduce injury risk, in the context of Paralympians with unique individual constraints.

Strengths and limitations

The exclusion of non-English language studies is a limitation of this study, given that it may have excluded studies from countries who typically finish high on the Paralympic Games medal tallies, including China, Russia and Iran. The restriction of only including elite Para sport athletes may have failed to identify useful learnings from non-elite or non-sporting applications of motor control. The characterisation of studies as being either biomechanics or motor control based, as judged by a single author, may be a limitation despite the delineation of the two subject areas being imprecise (Glazier et al., 2005). It may be that some of the studies using electromyography may have been characterised either way. Additionally, the MEPIS metric could dramatically change if the whole range of sports science research (i.e., psychology and physiology) where added to this review. The current scope of this review may be a strength in that it identified numerous gaps that highlight opportunities for future researchers to conduct focussed systematic reviews. Another strength is considered to be the use of the MEPIS metric to aid identification of gaps in research, and when combined with the classification of motor tasks across sports may present opportunities for research findings in a particular sport to apply to others with similar motor task demands. This review presents a snapshot in time, based on the sports & medal events inherent in the 2020 Tokyo Paralympic Summer Games and the 2022 Beijing Paralympic Winter Games and, as such, changes in eligible sports, medal events or other relevant factors will change the breadth and depth of identified gaps.

Conclusion

This review presented a broad overview of biomechanics and motor control research in the performance and injury domains from 237 studies of Paralympic sports. It identified important empirical and population gaps for individual sports, female participation, and the maturity of injury studies in terms of determination of mechanisms of injury and implementation of prevention strategies. Motor control research in general was under-represented and may benefit from the use of new technologies, including virtual reality. Future studies to fill these gaps may present opportunities for Paralympic stakeholders to yield improved outcomes.

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