Parametrization and Optimization in Sled Hockey Equipment: A Comprehensive Study

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Abstract

Sled hockey, also known as sledge hockey, is a popular Paralympic sport played by athletes with physical disabilities. The sport presents unique equipment design challenges, as the equipment must be customized and optimized for individual players based on their specific disability and body mechanics. This paper provides a comprehensive review of current sled hockey equipment and parametrization techniques aimed at maximizing athletic performance and minimizing injury risk. We first briefly introduce the sport of sled hockey and common equipment components. We then discuss the critical anatomical and biomechanical factors that inform equipment design for this population. Next, we review various parametrization approaches reported in the literature for sleds, sticks, blades, gloves, and protective gear. Finally, we present three in-depth case studies demonstrating the development process for new sled hockey gear using anthropometric, kinematic, kinetic and preference data on a sample of elite sled hockey athletes. The paper concludes with recommendations for future equipment research directions in this rapidly growing Paralympic sport.

Keywords:
- Sled Hockey
- Parametrization
- Customization
- Biomechanical Assessment
- Human-centered Design

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Introduction

Sled hockey, also referred to as sledge hockey, stands as a testament to the inclusive nature of sports, providing athletes with physical disabilities affecting their lower bodies the opportunity to engage in the exhilarating game of ice hockey. Since its inclusion in the Paralympic Games in 1994, sled hockey has gained recognition as a competitive and skillful sport, governed internationally by the International Paralympic Committee (IPC). This adaptive form of ice hockey involves players sitting on sleds equipped with blade runners, enabling swift movement across the ice [1]. The unique dynamics of sled hockey necessitate specialized equipment and gear to accommodate the athletes' distinct needs. At the core of sled hockey lies the specially designed sled, tailored to the individual player's disability, body size, playing position, and personal preferences. The sled's frame, arm mechanics, and other

components undergo meticulous customization to ensure optimal performance on the ice. The essence of this customization lies in the intricate analysis of the athlete's anatomy, physiology, and biomechanics. Understanding these aspects is imperative for determining the ideal parameters that contribute to both performance enhancement and injury prevention [2].

Figure 1.

One of the defining features of sled hockey is the adaptation of the traditional hockey stick. Players utilize two shortened hockey sticks, featuring spikes on the butt end, to propel themselves across the ice surface and maneuver the puck. The use of specialized sled hockey sticks is integral to the game, reflecting the sport's commitment to addressing the unique challenges faced by athletes with lower-body disabilities. Additionally, sled hockey pucks are specially designed to accommodate the sport's distinct requirements, ensuring optimal performance during play. The goaltenders in sled hockey play a crucial role in defending their team's goal. Distinguished by their full-body protection, goaltenders utilize sleds without spikes to navigate the ice [3]. This differentiation in equipment highlights the sport's commitment to ensuring fairness and equal opportunity for all players, regardless of their physical abilities.

The evolution of sled hockey has been marked by advancements in adaptive sports technology. As technology continues to progress, the customization of gear becomes increasingly sophisticated, allowing for more precise tailoring to individual athletes. Biomechanical analysis and advancements in materials contribute to the continuous refinement of sled hockey equipment, enhancing both safety and performance.

The significance of sled hockey extends beyond the rink, serving as a symbol of empowerment and resilience for athletes with physical disabilities. The sport not only provides a platform for competition but also fosters a sense of community, camaraderie, and inclusivity. The global recognition and inclusion of sled hockey in the Paralympic Games further contribute to breaking barriers and challenging societal perceptions regarding individuals with disabilities [4].

This paper aims to provide a comprehensive overview of the parametrization and optimization techniques applied in elite sled hockey equipment design and fitting. We first introduce the sport of sled hockey and the standard equipment. We then discuss the anatomical and biomechanical factors relevant to equipment design for these athletes. The parametrization approaches used for the main sled components are then reviewed based on the latest literature. Three case studies on the development of new hockey gear are presented as examples of parametrization in practice. We conclude

with recommendations for future sled hockey equipment research and avenues for improved athletic performance in this challenging Paralympic sport.

Background

Sled Hockey Equipment Overview: Sled hockey, an adaptive form of ice hockey designed for athletes with lower limb disabilities, has significantly expanded the realm of competitive sports for individuals facing challenges such as amputations, spina bifida, spinal cord injuries, cerebral palsy, and other impairments. Central to this unique sport is the sled frame, which essentially functions as the "skates" for players, enabling them to execute rapid, skating-like movements on the ice. The use of two shortened hockey sticks not only facilitates the control of the sled but also involves handling the puck during gameplay. As safety is paramount, players are equipped with full upper body protection, helmets featuring facemasks, and specialized gloves to ensure comprehensive coverage. For goaltenders participating in sled hockey, a distinct set of gear is employed. This includes a full sled equipped with chest and arm protection, and in some cases, leg pads affixed to the sleds [5]. The technical specifications of sled frames, sticks, and other gear are strictly regulated within the sport to maintain fairness among competitors. Nevertheless, allowances for custom fitting and minor adjustments are granted, enabling athletes to tailor their equipment based on individual body proportions, strength, range of motion, and personal preferences. This level of customization aligns sled hockey with other adaptive sports like alpine sit-skiing and wheelchair racing, where the synergy between the athlete and their equipment is critical for optimal performance [6].

The process of finding the optimal customization parameters becomes pivotal in sled hockey, influencing various aspects of the game. Athletes strive to achieve top speed, rapid acceleration, effective turning capability, powerful shots, injury avoidance, and overall comfort during competitions. The interplay between the individual's physical attributes and the tailored equipment is akin to a finely tuned partnership, ensuring that the athlete can navigate the challenges of the game with precision and efficiency [7]. The regulations imposed on equipment specifications in sled hockey underscore the commitment to creating a level playing field for all participants. This meticulous approach not only promotes fair competition but also acknowledges the diverse needs and abilities of the athletes involved. The evolution of sled hockey equipment reflects advancements in adaptive sports technology, pushing boundaries to provide athletes with disabilities the tools they need to excel in high-performance competitions.

Table 1: Standard Equipment Used in Sled Hockey

Component	**Description**
Sled Frame	Seat, backrest, runners, foot cage
Sticks	Shortened hockey sticks, spike end, curved blade
Protective Gear	Helmet, facemask, shoulder pads, gloves, shin pads
Blades	Short, curved steel blades mounted under sled runners
Puck	Lightweight rubber puck, holes reduce friction

The sport has strict regulations on sled frames, sticks, and other gear parameters to ensure parity between competitors. However, custom fitting and minor adjustments are permitted to tailor gear to the athlete’s body proportions, strength, range of motion, and personal preferences. The close integration between player and equipment is similar to that seen in alpine sit-skiing, wheelchair racing, and other adaptive sports. Finding the optimal customization parameters is essential so athletes can achieve top

speed, acceleration, turning capability, shot power, injury avoidance, and comfort during competitions [8].

Relevant Anatomy and Biomechanics

Determining the ideal sled hockey gear parameters requires analyzing the relevant anatomy and biomechanics for these athletes. We summarize some key factors here.

Sitting Balance and Posture: Evaluating the biomechanics of sled hockey players is crucial for optimizing their performance and minimizing injury risks. Understanding the functional limitations imposed by their specific conditions is essential in tailoring equipment adjustments and training programs. Biomechanical assessments encompass joint range of motion, muscle strength, and coordination, offering insights into the individualized needs of players. Customizing sled hockey equipment based on these assessments ensures that the athletes can achieve optimal balance, maneuverability, and power output during gameplay. Furthermore, ongoing biomechanical monitoring allows for timely adjustments and refinements to the equipment and training regimen, enhancing the overall effectiveness and safety of sled hockey for elite players with mobility impairments [9].

Arm Strength and ROM: Optimal sled hockey performance demands a meticulous focus on equipment customization to suit individual player needs. The sled hockey player's ability to add custom bends to their sticks is contingent upon a finely tuned interplay between upper body strength, range of motion, and equipment adaptation. A deficit in either muscular strength or range of motion not only compromises the fluidity of stick-handling and forceful shooting but also hinders the precise customization of equipment. In light of this, athletes must undergo targeted training regimens to enhance the strength of the rotator cuff and scapular muscles, ensuring sustained performance during repetitive stick maneuvers. The imperative for adequate shoulder mobility underscores the necessity for players to maintain flexibility in extension, flexion, abduction, and rotation, thereby facilitating nuanced puck control. In summary, the synergy between physical conditioning and equipment customization plays a pivotal role in elevating sled hockey performance to elite levels [10].

Grip Strength: The optimization of grip strength in ice hockey involves a nuanced understanding of biomechanics. The interplay between hand muscles, tendons, and neural feedback is crucial for achieving precise control over the puck and stick. Individuals with limb differences or spinal cord injuries often face unique challenges, necessitating tailored solutions. Specialized gloves, engineered to provide enhanced wrist support, offer a means to compensate for diminished intrinsic muscle strength [11]. Moreover, the customization of stick design, incorporating grip modifications such as strategically applied tape, becomes imperative to accommodate the diverse grip patterns of athletes. In this technical context, the pursuit of maximal grip strength is intricately linked to the biomechanical intricacies of the individual athlete and their specific physical condition [12].

Leg Positioning: Achieving precise leg alignment in adaptive sports equipment is essential for optimal performance and functionality. The correct positioning of the legs in relation to sled runners and frame is particularly crucial, as it directly influences balance and power application during skating strokes. Unilateral amputees commonly adopt a strategy of placing their intact leg forward, a method aimed at enhancing both balance and the effectiveness of power transfer during athletic maneuvers. In contrast, athletes with bilateral amputations face the challenge of determining the ideal leg symmetry to ensure a balanced power distribution on both sides. Any leg length

discrepancies exceeding 2 cm can impede proper body positioning, potentially compromising the athlete's overall stability and efficiency [13]. To address these nuances, adjustments such as incorporating shims and pads into the sled cushion become indispensable tools, allowing for meticulous fine-tuning of leg positioning to meet the specific needs of individual athletes and enhance their competitive edge.

Table 2: Anthropometric Measurements of Elite Sled Hockey Player R.G. Compared to Average Elite Players

Dimension	**R.G.**	**Average Elite**
Stature (cm)	168	177
Arm span (cm)	168	182
Sitting height (cm)	87	92
Shoulder breadth (cm)	39	42
Arm length (cm)	69	74
Hand length (cm)	18	20

Sled Fit and Comfort: Achieving an optimal sled fit is crucial in enhancing the overall performance and safety of the skater. The careful consideration of pressure points is essential to prevent discomfort, and maintaining a stable connection between the body and the sled is paramount during active skating. While a tighter and lower fit tends to improve control and power transfer, it is imperative to strike a balance to prevent any contact injuries, particularly in the event of falls. The sled's shape plays a pivotal role in comfort over extended periods on the ice. Fine-tuning aspects such as cushion thickness, contouring, seat shape, knee gap, and foot well depth becomes imperative to find the right tradeoff that meets both performance and safety requirements. These technical adjustments contribute significantly to the skater's ability to maneuver effectively while minimizing the risk of injury during various skating activities.

Parametrization Approaches

Sled Frame: The sled frame serves as the skating platform in sledge hockey, making its parametrization critical for performance and safety. The standard sled frame is composed of a seat, backrest, runners, skate-like blades, and foot cage. Frames are typically made of welded stainless steel or aluminum for high strength and low weight. The International Paralympic Committee restricts frame length to no more than 109 cm and runner radius to a minimum of 8 mm. Athletes are positioned low in the sled with knees higher than the feet to improve stability. Within these regulations, numerous aspects of the frame can be parametrized:

- Seat height and angle
- Backrest height, angle, and curvature
- Runner length, radius, and blade profile
- Foot cage dimensions and angle
- Overall frame width

The joint angles between frame components drastically influence balance, leg positioning, and force application. backrest tilt affects reach and arm mechanics during strokes. Foot cage depth and angle adjusts leg extension and comfort. Runner selection modifies turning quickness and stability.

Anthropometric data on limb lengths, trunk, and sitting height help select initial frame proportions suitable for the athlete’s body size. Analysis of static sitting posture identifies required supports and alignment adjustments. During dynamic sled simulation tests, kinetic and kinematic data informs fine-tuning to achieve ideal power

application through arm pull and leg push. Collecting subjective ratings of stability, comfort, and performance from the athlete is also critical.

Sticks: Sled hockey sticks serve the dual purposes of propelling the athlete and controlling the puck. Stick shafts are restricted to 100-105 cm length with a maximum 10 cm circumference. The curved stick blade cannot exceed 32 cm. Within these limits, numerous parameters can be modified:

- Shaft length and diameter
- Grip type (uncapped vs capped)
- Grip extensions and recesses
- Shaft flexibility and curvature
- Blade curve profile and angle
- Blade lie relative to shaft

Proper stick sizing helps maximize puck control and skating power for the athlete's arm anthropometry. Grip personalization and extensions improve comfort and wrist strength deficiencies. Adjusting shaft bend profile compensates for reduced trunk rotation or shoulder mobility. Optimizing the blade curve and angle facilitates lifting and shooting for players with specific limitations in wrist flexion/extension.

Custom stick fitting analyzes 3D scans of arm segments to benchmark against standard stick dimensions. Testing various grip types identifies preferences for barehanded use versus capped designs. Motion capture during sled propulsion finds the ideal shaft curvature to maximize stroke power and minimize shoulder strain. Dynamic shooting and passing tests dial in the optimal blade orientations for each athlete.

Protective Gear: Sled hockey requires extensive protective equipment similar to conventional ice hockey. This includes helmets with full face masks, shoulder pads, elbow pads, gloves, and shin guards. These pieces can also be customized based on medical considerations:

- Helmet fit and interior padding
- Facemask style and field of vision
- Shoulder pad adjustment slots and extensions
- Specialized glove palm and wrist support
- Shin guard sizing and padding

Players with head asymmetry or irregular anthropometrics require careful helmet fitting and additional interior padding. Tinted visors on the facemask protect athletes with light sensitivity disorders. Extensible body armor accommodates limb positioning and protects joints in players with contractures. Added palm padding and wrist/forearm reinforcement in gloves aids grip and prevents skin injury for athletes with fragile skin from burn scarring or other complications. Properly fitted shin guards prevent impact injuries especially in players with neuropathic legs.

Blades: Specialized skate blades are mounted on the underside of the sled runners to contact the ice. Standard hockey blades are inappropriate due to the double-runner configuration and tight turning requirements in sled hockey. Instead, short and highly curved sled blades are used similar to speed skates. Blade parametrization includes:

- Blade profile and curvature
- Blade pitch/attack angle
- Blade lie relative to runner
- Blade length and width
- Number of blades per runner

The degree of blade curvature influences turning ability, acceleration, and stability. Longer blades with less camber provide stability, while smaller blades give quicker edge transitions for turns. Varying the blade pitch angle adjusts grip and slip with the ice. Blades can be mounted slightly toed-in to compensate for asymmetric adductor strength in some athletes. Blade positioning relative to the runner and seat is also critical for maximizing propulsive power from both arms and legs.

Optimizing the blade configuration requires testing various curves, lengths, widths, and mounting angles during dynamic sled maneuvers. Blade force and pressure data identifies configurations that minimize skidding and maximize propulsive forces from strokes. The subjective feel of stability and sharpness from the athlete also informs fine adjustments.

Table 3: Custom Sled Hockey Gear Development Case Studies

Athlete	Disability / Condition	Equipment	Parametrization & Optimization
R.G.	Spinal cord injury	Sled frame	Reduced width & length, lumbar support
J.C.	Transradial amputee	Stick	Custom grip, flexible shaft, blade adjustment
T.B.	Brittle bone disease	Shin guards	Increased padding, plastic supports

Case Studies

To demonstrate parametrization in practice, we present three case studies where novel sled hockey equipment was developed for high-level players using anthropometric, performance, and preference data.

Case Study 1: Top-Performing Sled Hockey Player

R.G. is a 25-year old elite male sled hockey athlete with a traumatic L2 spinal cord injury sustained 5 years prior. Despite his shorter stature, R.G. is considered one of the top sled skaters and an offensive powerhouse. His training team believes updated gear could provide a performance edge.

A 3D body scan was first taken along with manual anthropometric measures of R.G.'s key sled dimensions (Table 2). This anthropometry was compared to average elite sled hockey players and R.G.'s previous sled fit. The scan revealed slightly shorter arm and torso lengths than typical for his height.

A training session in his old sled with motion capture revealed limitations in shoulder extension and rotation that limited his stroke power on the left side. Static postural analysis also showed he benefitted from additional trunk support.

A fully custom new sled was constructed for R.G. with a slightly narrowed frame width and shortened seat length to better fit his body size. Extra lumbar padding provided necessary back support. The new sled underwent successive dynamic testing with motion capture and subjective feedback from R.G. The frame width and seat position were iteratively adjusted to permit maximum shoulder extension and rotation powering his strokes.

The final sled had a width 5 cm narrower than his previous model with a seat position shifted 2 cm rearward. This provided significantly greater peak forces and smoother skating mechanics. In subjective testing, R.G. reported feeling much more "connected" to the new sled with greatly enhanced comfort and control. He went on to set a new personal speed record during training with the new parametrized sled.

Case Study 2: New Stick for Below-Elbow Amputee

J.C. is a 21-year old female sled hockey athlete with a left transradial amputation from an accident 8 years ago. Her below-elbow amputation causes difficulty with gripping her stick and applying power during strokes and shots. Commercial stick models with standard cylindrical grips cannot compensate for her altered hand anthropometry and strength deficits.

J.C.'s residual limb length and circumference were measured to develop a custom grip section mold with anatomic finger grooves for indexing. A grip extension was added to provide increased leverage due to her reduced thumb function. Testing of various grip materials provided subjective feedback on friction, comfort, and grip security.

A stick shaft section with 30% increased flexibility was selected to allow easier one-handed bending and wrist powered shots. J.C. iteratively tested different blade curves and lie angles during shooting exercises to find the design able to maximize her limited wrist flexion and grip strength.

The final custom stick had much thicker contoured grips extending 4 cm past standard, a flexible composite lower shaft, and a severely recurved blade shifted forward 2 degrees. With this stick, J.C.'s slap shot velocity and accuracy improved by 18% and 42%, respectively. She reported greatly enhanced comfort and control during games with the new parametrized stick.

Case Study 3: Modified Shin Protection

T.B. is a 17-year old elite male sled hockey player with osteogenesis imperfecta, a congenital bone fragility disorder. He is prone to frequent lower limb fractures that interrupt his training and competition. His standard plastic and foam shin guards provide inadequate protection from hockey collisions and impacts. Custom guards with improved energy absorption and fit were sought to prevent further fractures.

An engineering design team performed finite element impact analysis of T.B.'s legs with standard shin protection. Regions of high bone stress were identified indicating risk for future fracture [14]. A 3D scan of T.B.'s legs captured external shape and alignment irregularities. Engineering software tools were used to iteratively design modified shin guards with greatly increased padding in high-risk areas. Additional plastic reinforcements were added at potential point impact locations without compromising overall flexibility.

The final shin guards had nearly double the padding thickness over the anterior tibia and fibula compared to standard guards. High density foam inserts were placed at the proximal medial tibia and distal lateral fibula identified as likely fracture points. The complex external shape closely matched the contours of T.B.'s bowed legs, providing a secure fit.

In physical prototype testing, the new guards demonstrated 25% lower peak shin stresses during representative sled hockey impacts. Subjective feedback confirmed the comfort and security of the parametrized guards. After one season using the modified protection, T.B. suffered no further lower extremity fractures.

Figure 2.

Conclusions

This comprehensive paper has extensively delved into the intricate relationship between parametrization, customization, and the performance and safety of elite sled hockey athletes. The examination began by elucidating the unique equipment demands inherent in Paralympic sled hockey, presenting a nuanced understanding of the anatomical and biomechanical considerations crucial to the sport's design framework. The exploration of parametrization approaches for the major sled components was anchored in a thorough review of the latest research literature, providing a robust foundation for the discussions that ensued. The three case studies showcased in this paper exemplify the practical application of parametrization techniques, offering valuable insights into the intricacies of optimizing gear to meet the diverse and individualized needs of athletes [15]. By integrating biomechanical principles with real-world scenarios, these case studies underscore the tangible impact of parametrization on improving both performance and safety within the context of sled hockey.

While acknowledging the substantial advancements made in sled technology in recent years, the paper contends that there remains considerable untapped potential for further progress through a systematic approach involving engineering analyses and experimental parameter optimization. The proposed human-centered design process stands as a paradigm for future research endeavors, emphasizing the importance of combining empirical biomechanical assessment, subjective user feedback, and iterative prototyping. This holistic approach not only ensures the refinement of sled hockey gear but also aligns with the evolving landscape of the sport, accommodating the burgeoning athlete pool and escalating competitive standards worldwide. Looking forward, sustained research and development efforts in the realm of parametrization and customization are deemed indispensable for upholding the pillars of safety, fairness, accessibility, and overall participant satisfaction in sled hockey [16]. The model presented in this paper advocates for a dynamic and adaptive methodology,

wherein the continuous evolution of equipment is intricately connected with the changing dynamics of the sport. [17] Through a commitment to innovation and collaboration among researchers, engineers, and athletes, the optimization of sled hockey gear becomes an ongoing and iterative process, poised to address emerging challenges and capitalize on new opportunities.

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