SmartGroup

MSc Biomedical Engineering

Biomechanics in Sit-skiing

Improving the Spike user experience from a biomechanical perspective

A technical report

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1 Introduction

Company & Product Background

SmartGroup AS is a Norway-based company specialising in the development of adaptive sports equipment. The company is strongly research and development oriented, with a focus on personalised solutions that accommodate a wide range of user impairments and functional needs. One of SmartGroup's core products is the Spike, a sit-ski designed for double-poling cross-country skiing. The Spike can also be used for off-season training, with a 4-wheel set up.

The Spike is used internationally, with its main market in Norway and users in Canada, the United States, Australia, and France. The majority of users participate recreationally rather than competitively, although Spike is also used by elite athletes in Para cross-country skiing. A key feature distinguishing Spike from competing sit-skis is its high degree of adjustability, allowing the seating configuration to be adapted to the individual user's needs and preferences. Spike is available in two main seating configurations; seated and kneeled (see figure 1. This project focuses on improving the Spike sit-skiing experience from a biomechanical perspective.

Figure 1: Spike seated(left), Spike kneeled (right)

Project Aim

Because the majority of Spike users are recreational rather than competitive, this project was focused on this user group. A recurring challenge reported by recreational sit-skiers is early-onset fatigue, which can limit session duration and overall enjoyment. Sit-skiing places high demands on the upper body and trunk to generate propulsion, and small differences in technique and equipment setup can therefore have a large impact on perceived effort. However, many users have limited biomechanical guidance for understanding why fatigue occurs or how changes in technique and sitting configuration may improve efficiency and stability. At the same time, the available research on sit-skiing is relatively limited, with results spread across different athlete groups, impairment levels, and experimental setups. This makes it difficult for practitioners and users to extract clear, actionable direction from the literature alone.

The project is aimed to translate existing biomechanical knowledge into practical guidance for recreational Spike users and product development. It addressed the following research questions:

- RQ1: Which biomechanical and user-experience factors most strongly influence propulsion efficiency, stability, and fatigue in sit-skiing?
- RQ2: How can these factors be turned into practical decision support so users can make more informed choices about Spike configuration?

RQ1 was addressed through a structured literature review and user research (questionnaire). The outcome was a consolidated set of findings and requirements relevant to recreational sit-skiing, including factors linked to trunk use, upper-limb loading, stroke timing, stability demands, and perceived fatigue. These requirements were formulated to be useful both for users (technique and setup guidance) and for SmartGroup (product improvement priorities and adjustability needs).

RQ2 focused on reducing the "trial-and-error" approach that many recreational users rely on when setting up their sit-ski. A simplified 2D biomechanical sit-ski model was therefore developed to illustrate how key parameters (notably seat height and pole height) influence stroke mechanics and potential propulsion efficiency for a given user's body dimensions. This was motivated by user responses indicating that a most users rarely adjust seat height (60%), despite evidence that seating configuration can meaningfully affect performance and effort (see Section 4). The model is intended as a practical tool to support configuration decisions with clearer biomechanical reasoning, rather than relying mainly on subjective feel or fixed "rule-of-thumb" settings. To the author's knowledge, an accessible simplified 2D sit-ski model aimed at user decision support is not widely available in the existing sit-ski literature, which further supported the relevance of this approach.

This report presents the results of the project. Section 2 describes the research methods and the setup of the simplified 2D model. Section 3 presents the findings from the literature review and user research (questionnaire), and also reports the outcomes of the model optimisation. Section 4 summarises the project conclusions and consolidates the resulting list of requirements and provides recommendations for future research and for further model and product-development improvements relevant to SmartGroup.

2 Methods

Research

As mentioned, research conducted to answer RQ1 consists of a literature review and user research through a questionnaire.

Literature Review

The literature review includes selected papers on biomechanics in sit-skiing. In-depth papers on biomechanics in stand-up skiing were also included, in case relevant for comparison. A total of 13 papers were reviewed.

User research

A cross-sectional user study was conducted using an online questionnaire to assess sit-ski comfort, perceived performance, and common use-related challenges. The questionnaire included both closed-ended items (e.g., multiple-choice and Likert-scale ratings) and open-ended questions to capture quantitative ratings and qualitative feedback on user experience. It was distributed to 93 SPIKE users, and 18 complete responses were received (response rate: 19.4%). The collected data were used to describe overall user experience trends and to explore associations between user characteristics, usage patterns, and reported outcomes.

2D biomechanical sit-ski model

The Sit-ski model was build using the TMT-method. This method formulates equations of motion by transforming the full Newton–Euler equations into a minimal set of independent generalized coordinates using principles of virtual work and D'Alembert (1). This transformation implicitly accounts for constraint forces, avoiding the need to compute them explicitly. As a result, the method produces numerically stable equations of motion that are well suited for computer-based simulation of constrained multibody systems, such as the linked rigid body as our case (1).

Model description

The sit-skier is modeled as a planar multi-body system represented by three lumped point masses located at the associated CoM's for the body segments and two additional point masses representing the sit-ski and the ski pole see figure 2. The body segments are connected by joints with prescribed joint limits. The model is based on the double-poling technique described above. Because this technique is approximately symmetric between left and right, the system is modeled in 2D and assumed to be extendable to a realistic 3D scenario. The joint motion is therefore restricted to rotations about the z-axis and translations in the sagittal x–y plane.

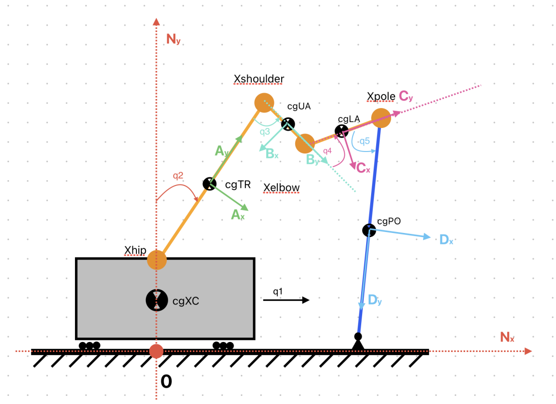


Figure 2: model

Since double poling is cyclic, the model is defined over a single pole stroke. During this stroke, the ski-pole tip is constrained to a fixed point on the ground, setting its position to $y = 0$ and a constant initial x-coordinate corresponding to the location of the pole plant. The sit-ski is constrained to translate only in the forward x-direction, with no lateral motion.

As no experimental motion data were available, the model was formulated in a forward-dynamics framework. Joint torques are used as inputs, while the forward translation in the x-direction and the ground reaction forces are obtained as outputs.

Model Structure and generalized coordinates

The model consists of five rigid bodies with lumped masses: sit-ski (seat and frame), trunk (including neck and head weight), upper arm lower arm and ski pole. These segments are each connect through the hip, shoulder, elbow and wrist joint, respectively.

Each body is assigned a mass and planar moment of inertia based on the lumped body mass and segment length. The following length parameters describe the main geometry of the model: seat height and length (H_{ss}&L_{ss}), seat angle (θ), trunk lenght (l_t), upper-arm length (l_{ua}) lower-arm length (l_{la}) and pole length (l_p).

Each lumped mass is assigned global $x-$ and y-coordinates that depend on the underlying joint rotations. To obtain a minimal-coordinate formulation, the positions and orientations of all lumped masses are expressed directly as functions of the generalized coordinates q, avoiding the need for additional joint-constraint equations (2).

The configuration of the system is described by five generalized coordinates:

$$\boldsymbol{q} = [q_1, q_2, q_3, q_4, q_5]^T \tag{1}$$

with associated generalized speeds $\mathbf{u} = \dot{\mathbf{q}}$

The global coordinates are expressed into generalized coordinates through

$$\boldsymbol{x} = T(\mathbf{q}) \tag{2}$$

where each lumped mass is defined in global coordinates as the position of a proximal reference point plus a rotated local offset.

Sit-ski CoM. The sit-ski translates only in the forward (x) direction:

$$\mathbf{r}_{S_o}(q) = \begin{bmatrix} x_{S_o}(q) \\ y_{S_o}(q) \end{bmatrix} = \begin{bmatrix} q_1 + \frac{L_{\text{ss}}}{2} \\ \frac{H_{\text{ss}}}{2} \end{bmatrix}.$$

Rotation matrix. Segment orientations are constructed using the 2D rotation matrix

$$R(\alpha) = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}.$$

Trunk CoM. The trunk is attached to the sit-ski through the trunk angle q_2:

$$\mathbf{r}_{A_o}(q) = \mathbf{r}_{S_o}(q) + R(q_2) \begin{bmatrix} 0 \\ \frac{l_t}{2} \end{bmatrix}.$$

Arm and pole segment CoMs. Using the same hierarchical formulation, the CoM of each following segment is defined by adding the rotated local offset to the previous segment's CoM:

$$\begin{aligned}
\mathbf{r}_{B_o}(q) &= \mathbf{r}_{A_o}(q) + R(q_2 + q_3) \begin{bmatrix} 0 \\ \frac{l_{\text{ua}}}{2} \end{bmatrix}, \\
\mathbf{r}_{C_o}(q) &= \mathbf{r}_{B_o}(q) + R(q_2 + q_3 + q_4) \begin{bmatrix} 0 \\ \frac{l_{\text{la}}}{2} \end{bmatrix}, \\
\mathbf{r}_{D_o}(q) &= \mathbf{r}_{C_o}(q) + R(q_2 + q_3 + q_4 + q_5) \begin{bmatrix} 0 \\ \frac{l_p}{2} \end{bmatrix}, \\
\mathbf{r}_{T_p}(q) &= \mathbf{r}_{C_o}(q) + R(q_2 + q_3 + q_4 + q_5) \begin{bmatrix} 0 \\ l_p \end{bmatrix}.
\end{aligned} \tag{3}$$

These expressions fully determine the global (x, y) coordinates of each lumped mass based solely on the minimal generalized coordinates q. Therefore, our $T(q)$ matrix is defined as:

$$\mathbf{T}(q) = \begin{bmatrix} \mathbf{r}_{S_o}(q) \\ \mathbf{r}_{S_g}(q) \\ \mathbf{r}_{A_p}(q) \\ \mathbf{r}_{A_o}(q) \\ \mathbf{r}_{B_p}(q) \\ \mathbf{r}_{B_o}(q) \\ \mathbf{r}_{C_p}(q) \\ \mathbf{r}_{C_o}(q) \\ \mathbf{r}_{D_p}(q) \\ \mathbf{r}_{D_o}(q) \\ \mathbf{r}_{T_p}(q) \end{bmatrix} \tag{4}$$

Here, S_g and T_p are the the points of contact of the sit-ski and ski pole (respectively) with the ground, and A_p, B_p,C_p,D_p are the hip, shoulder, elbow and wrist joints, respectively. They are defined based on the generalized coordinates in the same manner as the CoMs.

This leads to the Jacobian Matrix $\mathbf{T}$, which maps the global velocities to generalized velocities. Moreover, this matrix is also used within the $TMT - method$ to map the global mass and force matrices to mass and force matrices acting on the generalized coordinates q (2).

The Jacobian matrix $\mathbf{T}$ is obtained through the chain-rule:

$$\dot{\mathbf{T}}(\mathbf{q}, \dot{\mathbf{q}}) = \frac{\partial \mathbf{T}}{\partial \mathbf{q}} \, \dot{\mathbf{q}} = \mathbf{T} \, \dot{\mathbf{q}}. \tag{5}$$

Unconstrained Equations of Motion

The unconstrained equations of motion of the sit-skier multibody system is described according to

q_1	Horizontal translation of the sit-ski along the snow
q_2	Trunk angle with respect to the global frame
q_3	Shoulder flexion/extension angle
q_4	Elbow flexion/extension angle
q_5	Pole angle relative to the forearm
S_o	CoM Sit-ski
A_o	CoM Trunk
B_o	CoM Upper Arm
C_o	CoM Fore Arm
D_o	CoM Ski pole
T_p	Ski-tip

Table 1: Definition of generalized coordinates and point labels.

Newton's second law, in terms of the generalized coordinates:

$$\bar{\mathbf{M}}\ddot{\mathbf{q}} = \bar{\mathbf{F}} \tag{6}$$

Where the reduced mass matrix $\overline{M}$ is a transformation of the mass matrix from global to generalized coordinates:

$$\bar{\mathbf{M}} = \mathbf{T}^{\mathbf{T}}\mathbf{M}\mathbf{T} \tag{7}$$

and $\overline{F}$ is the reduced force matrix, defined as:

$$\bar{\mathbf{F}} = \mathbf{T}^{\mathbf{T}}(\mathbf{f} - \mathbf{M} \cdot \mathbf{g_{conv}}) + \mathbf{Q} \tag{8}$$

Here, f are global forces acting on the bodies, such as gravity and resistance forces. Q are the forces exerted on the local, generalized coordinate frames. These include forces acting on the joints, such as joint torques, stiffness, and damping. Further, g_{conv} is the convective acceleration terms of x (2). The convective acceleration refers to the acceleration of a body experienced due to its motion within a moving reference frame, which is distinct from the frame's overall acceleration.

Within the sit-ski multi-body system, these elements are defined as follows:

$$\mathbf{M} = \operatorname{diag}\big(\mathbf{M}_{S_o}, \mathbf{M}_{S_g}, \mathbf{M}_{A_p}, \mathbf{M}_{A_o}, \mathbf{M}_{B_p}, \mathbf{M}_{B_o}, \mathbf{M}_{C_p}, \mathbf{M}_{C_o}, \mathbf{M}_{D_p}, \mathbf{M}_{D_o}, \mathbf{M}_{T_p}\big) \tag{9}$$

Where each lumped point mass (CoM of each segment) is defined as a mass in the x, y direction and an associated mass moment of inertia I_z about that CoM.

$$\mathbf{M}_{S_o} = \begin{bmatrix} m_{ss} & 0 & 0 \\ 0 & m_{ss} & 0 \\ 0 & 0 & I_{z,S_o} \end{bmatrix}, \tag{10}$$

The joint are massless markers and defining the segment geometry and therefore not given a mass in mass matrix.

$$\mathbf{M}_{A_p} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \tag{11}$$

The external force vector $\mathbf{f}$ acting on each body segment consists of gravity, aerodynamic drag and rolling resistance. For each segment CoM $(S_o, A_o, B_o, C_o, D_o)$ a gravitational force acts in the negative global y-direction and a drag force opposes the segment's velocity. At the sit-ski contact point S_g a rolling resistance force opposes the forward motion. The massless joint points (A_p, B_p, C_p, D_p) are treated as massless markers and therefore do not carry external forces.

The aerodynamic drag force on each segment $i \in \{S_o, A_o, B_o, C_o, D_o\}$ is modelled as

$$\mathbf{F}_{\text{drag},i} = -\tfrac{1}{2}\,\rho\, c_{D,i}\, A_i\, \|\mathbf{v}_i\|\, \mathbf{v}_i, \tag{12}$$

where ρ is air density, $c_{D,i}$ a drag coefficient, A_i the frontal area and $\mathbf{v}_i$ the velocity of segment i expressed in the global frame. The rolling resistance at the sit-ski contact point S_g is given by

$$\mathbf{F}_{\text{roll}} = -c_{\text{rr}}\, N_{\text{normal}}\, \hat{\mathbf{v}}_{\mathbf{sign}}(v_{S_g,x})\, \hat{\mathbf{n}}_x, \tag{13}$$

with c_{rr} the rolling-resistance coefficient, $N_{\text{normal}} = m_{\text{total}}g$ the normal force, $\hat{v}_{sign}$ the velocity direction of S_g in the global x-direction, and $\mathbf{e}_x$ as the belonging unit vector.

The resultant external force on each point is then

$$\mathbf{R}_{S_o} = -m_{ss}\, g\, \hat{\mathbf{n}}_y + \mathbf{F}_{\text{drag},S_o}, \tag{14}$$
$$\mathbf{R}_{S_g} = \mathbf{F}_{\text{roll}}, \tag{15}$$
$$\mathbf{R}_{A_o} = -m_t\, g\, \hat{\mathbf{n}}_y + \mathbf{F}_{\text{drag},A_o}, \tag{16}$$
$$\mathbf{R}_{B_o} = -m_{ua}\, g\, \hat{\mathbf{n}}_y + \mathbf{F}_{\text{drag},B_o}, \tag{17}$$
$$\mathbf{R}_{C_o} = -m_{la}\, g\, \hat{\mathbf{n}}_y + \mathbf{F}_{\text{drag},C_o}, \tag{18}$$
$$\mathbf{R}_{D_o} = -m_p\, g\, \hat{\mathbf{n}}_y + \mathbf{F}_{\text{drag},D_o}, \tag{19}$$
$$\mathbf{R}_{A_p} = \mathbf{R}_{B_p} = \mathbf{R}_{C_p} = \mathbf{R}_{D_p} = \mathbf{R}_{T_p} = \mathbf{0} \tag{20}$$

where $\mathbf{n}_y$ is the unit vector in the global y-direction.

Stacking the x-, y- and z-components of each point force yields the global force vector

$$\mathbf{f} = \begin{bmatrix} \mathbf{R}_{S_o} \\ \mathbf{R}_{S_g} \\ \mathbf{R}_{A_p} \\ \mathbf{R}_{A_o} \\ \mathbf{R}_{B_p} \\ \mathbf{R}_{B_o} \\ \mathbf{R}_{C_p} \\ \mathbf{R}_{C_o} \\ \mathbf{R}_{D_p} \\ \mathbf{R}_{D_o} \\ \mathbf{R}_{T_p} \end{bmatrix} \in R^{33}, \tag{21}$$

where each $\mathbf{R}_{(\cdot)} = [f_x,\, f_y,\, f_z]^\mathsf{T}$ is expressed in the global frame.

Further, the forces exerted on the local coordinates ($\mathbf{Q}$) constist of joint torques, stiffness and damping for each joint i, each defined as:

$$Q_i = B_i + K_i + \tau_i + \tau_{lim,i} \tag{22}$$

where

$$Bv_i = -b \cdot u_i \tag{23}$$

$$Kv_i = -k \cdot (q_i - q_0) \tag{24}$$

Here, b and k are the damping and stiffness constants, respectively.

$$\tau_i(t) = \int_0^t \tau_c, dt \tag{25}$$

where τ_c is the given torque to the joint.

Lastly, the convective acceleration is defined as follows:

$$\mathbf{g}_{\text{con}} = \mathbf{M} \cdot \frac{\partial \mathbf{T}}{\partial \mathbf{q}}\, \dot{\mathbf{q}}\, \dot{\mathbf{q}} \tag{26}$$

Constraint equation

Since the model represents only a single pole stroke, the ski-tip must remain fixed at its initial position throughout the motion.This imposes a constraint in both x- and y-directions. Specifically, the ski-tip should not move horizontally from its initial x position and should remain aligned with the global y-axis. This constraint can be formulated as:

$$fh = \begin{bmatrix} fh_x \\ fh_y \end{bmatrix} = \begin{bmatrix} \mathbf{r}^{\mathbf{tp/0}} \cdot \hat{\mathbf{n}}_{\mathbf{x}} - \mathrm{x}_{\text{tip}} \\ \mathbf{r}^{\mathbf{tp/0}} \cdot \hat{\mathbf{n}}_{\mathbf{y}} \end{bmatrix} = 0 \tag{27}$$

To include these holonomic constraints in the equations of motion, they are differentiated twice with respect to time to express them in terms of generalized accelerations (3). This results in:

$$\ddot{\mathbf{f}}_h = \begin{bmatrix} \ddot{\mathbf{r}}^{\text{tp}/0} \cdot \hat{\mathbf{n}}_x \\ \ddot{\mathbf{r}}^{\text{tp}/0} \cdot \hat{\mathbf{n}}_y \end{bmatrix} = \mathbf{0} \tag{28}$$

By taking the Jacobian of this expression with respect to the generalized accelerations $\ddot{q}$, we obtain the constraint formulation:

$$\mathbf{C}\ddot{\mathbf{q}} = -\mathbf{C}_{\mathbf{con}} \tag{29}$$

$\mathbf{C} = \dfrac{\partial \ddot{\mathbf{f}}_h}{\partial \ddot{\mathbf{q}}}$ is the constraint Jacobian,

$\mathbf{C}_{\text{con}}$ is the convective acceleration term resulting from the time-varying velocities and orientations of the ski-tip.

The constraint equation can then be incorporated into the equation of motion, leading to the following formulation:

$$\begin{bmatrix} \overline{\mathbf{M}} & C^T \\ C & 0 \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}} \\ \lambda \end{bmatrix} = \begin{bmatrix} \overline{\mathbf{F}} \\ -\, C_{\text{con}} \end{bmatrix} \tag{30}$$

Here, λ contains the Lagrange multipliers, representing the generalized forces required to satisfy the ski-tip constraint.

Solving the system

The system's joint accelerations can be solved from (30) by re-ordering the equation:

$$\begin{bmatrix} \ddot{\mathbf{q}} \\ \lambda \end{bmatrix} = \begin{bmatrix} \overline{\mathbf{M}} & C^T \\ C & 0 \end{bmatrix}^{-1} \begin{bmatrix} \overline{\mathbf{F}} \\ -\, C_{\text{con}} \end{bmatrix} \tag{31}$$

The joint trajectories of the sit-skier model can be obtained from the joint accelerations $\ddot{q}$ and constraint forces λ by numerically solving the system's equations of motion using the Euler integration method.

The equations of motion are expressed as a system of first-order ordinary differential equations:

$$\dot{\mathbf{x}}(t) = f(t, \mathbf{x}(t), \mathbf{p}), \tag{32}$$

where $\mathbf{x}(t)$ is the state vector comprising generalized coordinates and velocities, and $\mathbf{p}$ is the set of constant system parameters.

The state vector is defined as:

$$\mathbf{x} = [q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad u_1 \quad u_2 \quad u_3 \quad u_4 \quad u_5]^T, \tag{33}$$

with q_i denoting the generalized coordinates and $u_i = \dot{q}_i$ their respective velocities.

In the explicit Euler method, the state is advanced using a fixed time step Δt by evaluating the derivative function once per step:

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \Delta t, f(t_k, \mathbf{x}_k, \mathbf{p}), \tag{34}$$

where t_k and x_k denote the time and state at step k, respectively. In this work, Euler integration is applied over the simulation interval with a uniform discretization of the time domain.

Model inputs

As mentioned, this forward-dynamic model of the sit-skier is driven by its joint torques inputs. These joint torques are parameterized in the form of step functions where:

$$\tau_i(t) = \begin{cases} A_i, & t_{1,i} \le t \le t_{2,i}, \\ 0, & \text{otherwise}. \end{cases} \tag{35}$$

This applies to all joints of the sit-skier, with generalized coordinates $q2 - q5$ resulting in a forward motion $q1$.

Further, other model parameters are defined to drive the forward dynamics. These include

- Physical parameters (i.e. body segment lengths, masses, joint stiffness's and damping, resistance coefficients)
- Initial conditions of the generalized coordinates (position and speed)
- Joint limits

Optimization of sit-ski configuration

The model is used to investigate the optimal sit-ski configuration for efficient propulsion during double-poling. Two physical parameters are selected as design variables: the seat height h_{ss} and the ski pole length l_p. These are among the most commonly adjusted setup parameters in real sit-skiing and are expected to have a significant influence on biomechanical performance.

The overall optimization is formulated in two stages:

1. **Torque-pattern identification:** The sit-skier is modeled in a forward dynamics framework, where joint torques act as control inputs that drive the motion. In the first stage, an optimal set of torque parameters is identified to generate efficient propulsion over a prescribed time horizon.
2. **Equipment configuration optimization:** Using the torque pattern obtained in Stage 1 as a fixed input, the second stage optimizes the equipment configuration (h_{ss} and l_p) to maximize performance.

In both stages, the performance objective is to maximize the forward distance traveled by the sit-ski, measured by the change in the generalized coordinate q_1 over the simulation interval $[t_0, t_f]$. This is implemented as a minimization problem by defining the following cost function:

$$J(x) = \left(q_1(t_f; x) - x_{\text{target}}\right)^2, \tag{36}$$

where x denotes the decision variables. For Stage 1, the decision vector contains the parameters of the joint-torque step functions,

$$x = \{A_i,\ t_{1,i},\ t_{2,i}\}_{i=2}^{5},$$

with $\tau_1(t) \equiv 0$. For Stage 2, the decision vector is

$$x = (\ell_p,\ h_{\text{ss}}).$$

The optimization is subject to model constraints (e.g., kinematic constraints, contact conditions, and joint limits) and bounded design variables:

$$\begin{aligned} &A_2 \in [-10,\ 300], && t_{1,2}, t_{2,2} \in [0,\ t_f], \\ &A_3 \in [-100,\ 100], && t_{1,3}, t_{2,3} \in [0,\ t_f], \\ &A_4 \in [-100,\ 100], && t_{1,4}, t_{2,4} \in [0,\ t_f], \\ &A_5 \in [-50,\ 50], && t_{1,5}, t_{2,5} \in [0,\ t_f]. \end{aligned} \tag{37}$$

Initial guesses were chosen as realistic torques for each joint:

$$\mathbf{x}_0 = \begin{bmatrix} 200.0 & 0.5 & 1.5 \\ -50.0 & 1.0 & 2.0 \\ -60.0 & 1.5 & 2.5 \\ 2.0 & 2.0 & 3.0 \end{bmatrix} \tag{38}$$

For each candidate parameter set x the system dynamics are numerically integrated over $[t_0, t_f]$ to obtain $q_1(t_f; x)$. The optimization is performed using the SciPy library, specifically `scipy.optimize.minimize`. The SLSQP method can be used for this optimization as it is a problem linear in its parameters.

3 Results, Analysis & Discussion

Literature Research

An overview of the results of the literature research is given in appendix 1. In total 13 articles related to the biomechanics in sit-skiing or cross country skiing were reviewed. Most of these studeis included high-levele motion studies, gaining insights into the biomechanics of double poling (sit)-skiing. The resutls of this analysis is distributed in multiple categories which is discussed in the next sections.

Disability classifications Five articles report on the disability classifications and how it affects sit-ski configuration and performance. Double poling sit-skiing recognizes different classes of disability, called the 'Loco Winter' classes (4) which is identified from LW10-LW12.

LW classification strongly affects both sit-ski performance and what kind of seating position an athlete can use, mainly because classes differ in trunk control. In LW10, athletes often show little or no activation of the rectus abdominis (core muscle) before poling, while LW12 athletes typically activate this muscle before the poling phase, helping them stabilize the trunk and transfer force into the poles more effectively (5). These differences show up in movement: trunk range of motion is generally larger in LW11–LW12 monolateral amputees than in LW10 athletes and LW12 bilateral amputees (6). Moreover, having functional abdominal and back extensor muscles, and therefore a higher trunk range of motion (ROM), is linked to stronger force production. When these muscles are missing, athletes often need more supportive sledge/seat designs to stay stable (6). Overall, performance increases from LW10 to LW12, and higher maximum speed is linked to larger trunk flexion ROM, better pole angle, and higher propulsive impulse (7). Field observations also show that trunk movement increases with higher class level in both forward–back and side-to-side directions (8). Because trunk function is so important, some studies propose that classification should include objective tests of trunk stability, such as checking reflex activity in the abdominal muscles during forward/backward perturbations (5).

Sit-ski sitting position Three studies reported that sit-ski seating configuration substantially influences propulsion and performance, primarily by constraining or enabling trunk motion. In particular, a seated configuration limits trunk range of motion (ROM) compared with the kneeled configuration (5)(6). This is specifically the case when the knees are positioned above the hips and the legs are maintained in a curled-up posture, which restricts trunk flexion (6). For athletes with higher levels of impairment (LW10–LW11), the knee-high position is commonly adopted because it increases trunk stability and reduces the risk of forward collapse (5). Consistent with this, the kneeled position has been linked to higher propulsive force and greater maximum speed, likely due to the increased contribution of coordinated trunk and upper-limb flexion–extension during the propulsion phase (9).

Poling technique and cycle characteristics Across studies, the sit-ski double-poling cycle is described in three phases: poling (PP), transfer (TP), and recovery (RP) (6). PP begins at maximum body/arm extension and ends at peak sit-ski velocity; TP ends when the poles leave the snow at maximum elbow extension; RP runs from elbow flexion until the next pole plant (6). Cycle time (CT) is the time between pole plants, poling time (PT) is pole contact time, and the duty cycle (DC = PT/CT) reflects how much of the cycle is spent producing propulsion, with higher DC indicating more time dedicated to propulsion (10).

Terrain has a clear influence on poling technique. In uphill skiing, a larger proportion of the cycle is dedicated to propulsion, resulting in longer poling times, shorter recovery times, and a higher duty cycle compared to flat terrain (10; 11). This allows more work to be delivered to the ground per cycle. Poling angle also plays an important role: increasing pole angle leads to greater elbow and trunk range of motion, producing longer and faster strokes. While this increases power output by directing more force forward, it also increases shoulder extension demands due to a larger moment arm and can reduce overall efficiency if the angle becomes too large (12).

Force application during pole plant follows a characteristic pattern. An initial impact force peak occurs just before the maximum active pole force, which likely serves to preactivate muscles and increase joint stiffness at the start of the poling phase (13). At higher skiing speeds, a shorter time to peak pole force (TPPF) is associated with better work economy, indicating that faster skiers benefit from reaching high forces quickly rather than spreading force over a long contact time (13).

Differences between faster and slower skiers further highlight the importance of timing and positioning. Faster skiers generate peak pole force later in the poling phase, when pole angle is more favorable for forward propulsion, whereas slower skiers rely more on impact forces at pole plant (14). More vertical pole plants reduce efficiency because the pole is planted closer to the body, shortening poling time and reducing impulse. In contrast, faster skiers place the poles farther forward, allowing longer poling times, greater cycle lengths, and more time to build force later in the stroke (14).

Kinematics in sit-skiing Results from sit-ski studies show a consistent kinematic pattern across the poling cycle. Trunk oscillation is greatest at the end of the poling phase (PP) and lowest during the middle of the recovery phase (RP), indicating that trunk motion is most involved during propulsion and reduced during recovery (6). When athletes are able to move and control their trunk, shoulder abduction remains limited (reported up to 45° in the most flexed position), suggesting that large shoulder abduction is not required for effective sit-ski poling when trunk control is sufficient (15). Wrist kinematics also show clear timing features, with rapid adduction–abduction near the end of the poling phase and rapid extension–flexion during recovery, supporting efficient pole release and repositioning (15).

Upper-limb kinematics at pole plant and during loading are strongly linked to force production. More flexed elbows at pole plant followed by a faster and larger elbow motion during the eccentric part of loading is associated with a stronger stretch–shortening preload of the triceps brachii, enabling greater elastic energy storage and a more forceful concentric push. Again, the trunk ROM plays a crucial role here, as more bending of the hip (forward lean) allows for more bent elbows at poling. This pattern is linked to higher peak pole force, higher impulse, longer push-off time and higher double-poling velocity (13). Finally, sit-ski measurements indicate that movement asymmetry is most pronounced at the start of the cycle and during uphill skiing (when demands are higher), which may represent avoidable energy losses and highlights the value of technique consistency and equipment setup that reduces asymmetric loading (16).

Muscle activation in sit-skiing To summarize the literature on muscle activation strategies in sit-skiing, and to compare these patterns with stand-up skiing, a comprehensive overview of the muscle activation was created (See figure3). The overview shows a clear shift in how propulsion is produced when moving from stand-up to sit-skiing. In stand-up skiing, the poling phase is supported by strong trunk flexion during the poling phase, combined with high activation of the arm push pattern (shoulder/arm extension + adduction) and elbow extension later in the poling phase. At the same time, there is a large contribution from the lower body (notably hip extension and ankle plantar flexion) across most of the poling phase. indicating that whole-body movement supports force production and efficient acceleration in stand-up skiing (13).

In sit-skiing (LW12) the lower-body contribution is absent, and the pattern becomes more upper-body dominated. Trunk flexion is present but appears more moderate and sustained through the poling phase. The strongest muscle activation is concentrated in the upper-limb chain, especially arm extension/adduction peaking around mid poling, and a pronounced elbow extension contribution toward the late poling phase. In addition, shoulder-related rows indicate a greater role for shoulder extension/external rotation/horizontal abduction and stabilizing functions during poling, consistent with higher demands on the shoulder complex then when compared to stand-up skiing (5).

User research

In total, 18 users completed the questionnaire. Given that Spike has more than 93 users, this corresponds to a response rate of approximately 20%. The results should therefore be interpreted with caution, as the limited sample size may not be fully representative of the overall user population.

All results of the questionnaire are included in Appendix 2.

Overall User experience

Overall, the user experience associated with the Spike is extremely positive, see figure 4a. Users generally enjoy riding the on the Spike, with a minimum amount of users reporting on discomfort and fatigue. Most discomfort related issues seem to be related to the arms and shoulders, where specific users also mentioned to have knee

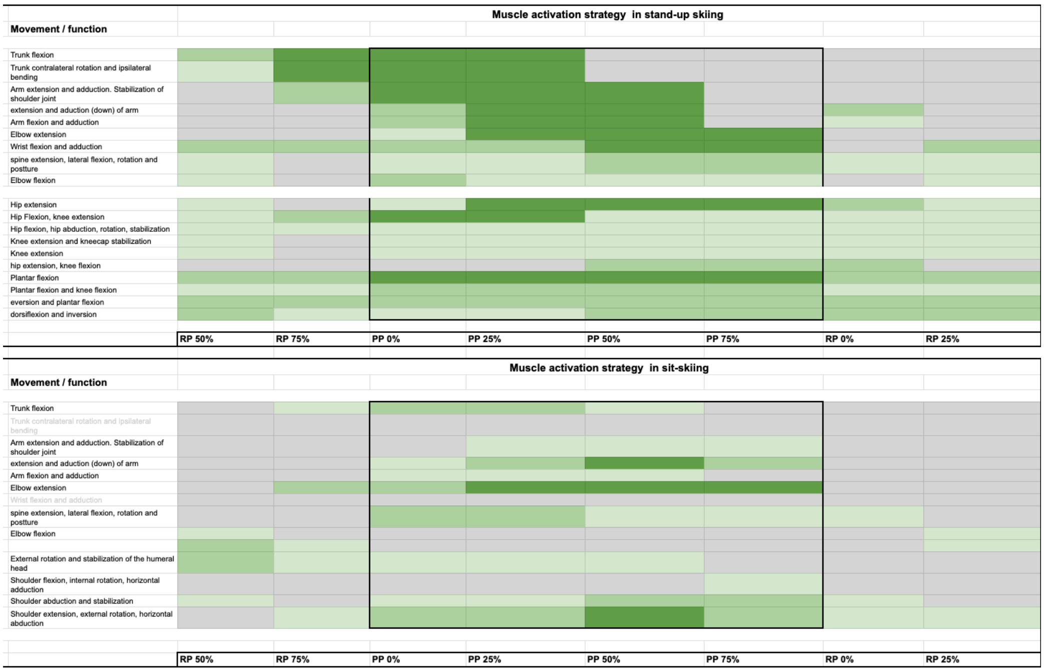


Figure 3: Muscle strategy in stand-up skiing (13) and sit-skiing (5),(17),(18)

problems (due to the pressure on the support) and trunk/ back pain, see figure 4b. This aligns with literature research, finding that most strain is put on the shoulders and arms for propulsion, leading to possible fatigue or discomfort problems.

Physical Ability and User experience

Most respondents reported good trunk control, while 16/18 reported reduced strength or sensation, primarily in the lower body, and a smaller subset also in the upper limbs (e.g., shoulders/hands). Users with upper-limb limitations tended to report higher fatigue and more discomfort, whereas those without upper-limb impairment more often reported low fatigue and little to no pain, suggesting that arm and core capacity may influence perceived fatigue. However, these patterns should be interpreted cautiously, as the results are not statistically significant.

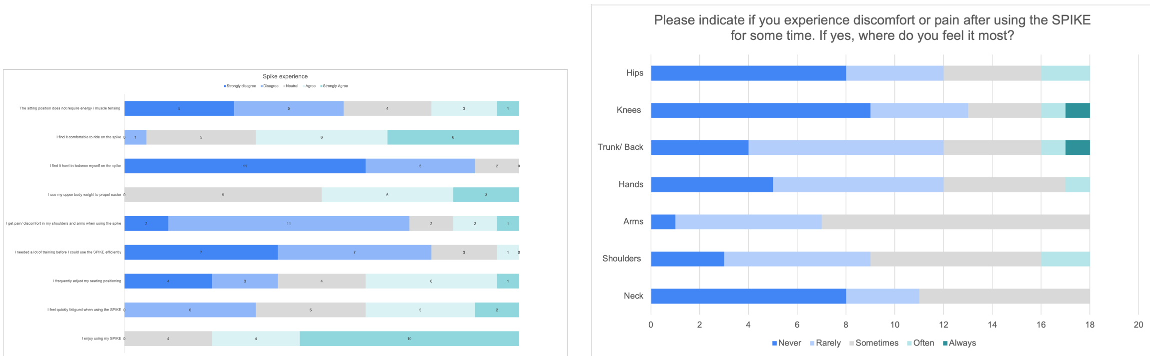
Despite variation in physical ability, no respondents felt completely unstable: most disagreed that they “find it hard to balance” on the Spike. The one user who strongly agreed they frequently adjust their position also reported the highest fatigue and discomfort and had notable physical limitations, suggesting that reduced capacity may increase the need for repositioning to maintain comfort and stability.

Influence of Spike Model and accessoires

Users were divided between the Kneeling SPIKE (n=14) and the Seated SPIKE (n=4). This distinction was associated with differences in perceived stability and comfort. All seated-model users reported feeling “Very Stable”, while kneeling-model users ranged from Very Stable to Neutral. Although no kneeling users felt unstable, around 20% reported only neutral stability, compared to none in the seated group.

Qualitative feedback suggests that kneeling users rely more on core engagement and frame contact for balance, which can feel less secure for some. Several kneeling users explicitly suggested improvements such as knee straps or better seat cushioning, indicating a need for additional support to improve comfort and stability.

About one-third of respondents used accessories, most commonly a vacuum cushion, sometimes combined with supports such as a backrest, elastic belt, or thigh supports. Users with such supports generally reported higher comfort, less frequent repositioning, and lower fatigue, whereas some users without accessories noted minor issues such as soreness or sliding over time. While no users felt unsafe without



(a) Spike experience

(b) Areas of discomfort

Figure 4: Questionnaire Results User Experience

accessories. These findings suggest that supportive accessories play a preventative role, reducing cumulative strain during longer rides. This highlights an opportunity to offer more integrated or optional support solutions, particularly for the kneeling Spike, to better accommodate users with lower core strength or longer usage durations.

Propulsion and stabilization techniques

All respondents propel the SPIKE primarily with their arms, as expected. However, more than 50% also reported using upper-body weight/core engagement to make propulsion easier, and none disagreed. This suggests many users develop an efficient technique that likely helps reduce arm fatigue during longer sessions.

For stabilization, users mainly rely on the core/trunk. Kneeling-model users appear to require more active bracing core activation to stay stable, while seated-model users benefit from passive support from the seat/backrest and therefore need less continuous muscle activation.

Overall, balancing does not seem to be a major challenge: only 2/18 reported any difficulty (neutral rather than poor), and no one agreed that balancing the SPIKE is hard. This indicates that most users quickly learn how to combine arm propulsion with core-based stabilization to ride stable.

Duration and Frequency of Use

Respondents ranged from very frequent users (several times per week) to occasional users (once a month or less). Usage frequency did not show a simple linear relationship with fatigue. Many regular and long-term users reported feeling only mildly fatigued, likely reflecting physiological adaptation, improved technique, and increased endurance. In contrast, some infrequent users reported higher fatigue, suggesting that limited conditioning may increase perceived exertion.

Exceptions were observed, notably among some highly frequent users who reported significant fatigue and discomfort. These users often described training-oriented goals, indicating that higher fatigue may reflect intentional high-intensity use rather than limitations of the Spike itself. This highlights that user goals and riding intensity influence outcomes alongside usage frequency.

After a typical session, most users described feeling mildly fatigued rather than exhausted. Discomfort, when present, was most commonly reported in the arms and shoulders, consistent with their primary role in propulsion. Trunk-/back and hand discomfort were also reported, particularly during longer rides, while knee and hip discomfort was least common, even among kneeling users, suggesting adequate support and padding for most.

The onset of discomfort varied between users, but often occurred after approximately one hour of continuous use. This indicates that most users remain comfortable during shorter sessions, whereas longer rides may benefit from rest breaks or ergonomic improvements to reduce cumulative strain during extended use.

2D sit-ski Model results

The aim of the sit-ski model was to identify an optimal pole length and seat height based on the model mechanics and prescribed inputs, so that users can make a more informed choice of sit-ski configuration.

However, with the current model formulation the proposed optimization approach was not able to converge to a meaningful local or global minimum for a given torque pattern. The main reason is the way the holonomic constraint was implemented: the ski-pole tip was enforced to remain fixed to the ground at a prescribed horizontal position x_{tip} As the sit-skier moved forward, this constraint generated a ground-reaction force at the pole tip that effectively pulled the system backwards in the negative x-direction. This produced an oscillatory response in the forward translation coordinate q_1 (see Fig. 5). The same effect is visible in the computed ground-reaction force, where the horizontal and vertical component become negative during forward motion (see Fig. 6), indicating that the constraint is opposing the intended direction of travel by effectively "pulling" on the sit-skier. As a consequence, the simulated dynamics became dominated by the constraint reaction rather than the applied torque pattern which caused the optimization to fail.

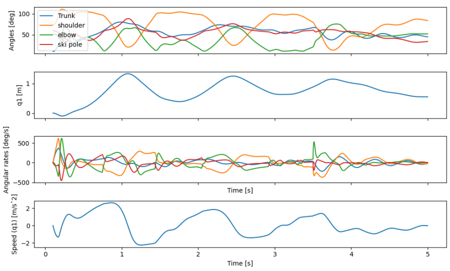


Figure 5: Joint trajectories plot

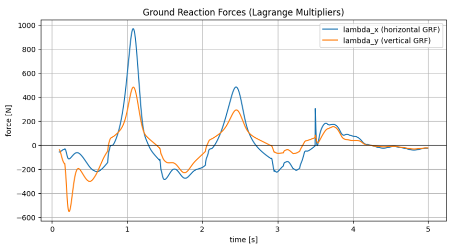


Figure 6: Ground reaction force plot

Alternative optimization approach

A slightly different approach to the optimization problem was investigated where the sit-ski geometry was determined that minimizes muscular effort during a forward propulsion task, while achieving a prescribed forward displacement and respecting joint limits. The two parameters pole length l_p and seat height H_{ss} are again considered as design variables.

The optimization problem minimizes a composite cost function consisting of three terms: effort, task accuracy, and joint limit penalties.

Effort term Muscular effort is approximated by the time integral of squared joint torques. Only actuated joints are included (excluding translational degrees of freedom):

$$J_{\text{effort}} = \int_{t_0}^{t_f} \sum_{i=2}^{5} \tau_i^2(t)\, dt \;\approx\; \Delta t \sum_{k=1}^{N-1} \sum_{i=2}^{5} \tau_{i,k}^2. \tag{39}$$

Distance constraint To enforce a desired forward displacement d_{target} at the end of the simulation, a quadratic penalty is applied to the final position of the translational coordinate q_1:

$$J_{\text{dist}} = w_d \left(q_1(t_f) - d_{\text{target}}\right)^2, \tag{40}$$

where w_d is a weighting factor.

Joint limit penalty Soft penalties are used to discourage violations of joint limits. For each joint q_i, violations of lower and upper bounds are penalized as

$$J_{\text{limits}} = w_q \sum_k \left[\max(0, q_{\min,i} - q_{i,k})^2 + \max(0, q_{i,k} - q_{\max,i})^2\right], \tag{41}$$

with weighting factor w_q.

Total cost The total objective function is therefore

$$J(\mathbf{x}) = J_{\text{effort}} + J_{\text{dist}} + J_{\text{limits}}. \tag{42}$$

The problem is solved using a bound-constrained quasi-Newton method (L-BFGS-B).

This optimization actually resulted in a minimization of the pole length, whilst the seat height stayed constant. This outcome could be explained by several factors:

- With shorter poles, the pole is planted at a more forward-inclined angle, which allows a larger portion of the applied force to contribute directly to forward motion rather than being directed vertically into the ground. As a result, propulsion becomes mechanically more efficient.

- In addition, shorter poles reduce the distance between the line of action of the pole force and the shoulder and elbow joints. This leads to smaller moment arms and therefore lower joint torques for the same propulsive effect. In contrast, longer poles increase these moment arms, requiring higher muscular effort at the shoulder and elbow to generate the necessary forces.
- Although longer poles increase reach, this advantage does not improve task performance in the present optimization, where the required forward displacement is fixed. Any additional reach beyond what is necessary therefore provides little benefit while increasing joint loading and overall effort. Consequently, the optimizer selects a pole length that prioritizes efficient force transmission and reduced torque demands rather than maximizing reach.

However, the accuracy of this model must be validated through motion studies.

Alternative tip-ground contact modeling

To address the limitations introduced by the holonomic pole-tip constraint, an alternative contact formulation was explored in which the ski-pole tip is no longer constrained to a single fixed point for the entire duration of the simulation. Instead of enforcing a kinematic constraint, the interaction between the pole tip and the ground is modeled using a collision model (3).

In this formulation, contact between the pole tip and the ground is resolved in the vertical (y-)direction using a compliant contact model. When the pole tip penetrates the ground plane, a normal contact force is generated based on a linear spring–damper relationship. Let Y_{Tp} denote the vertical position of the pole tip relative to the ground, and $\dot{Y}_{\mathrm{Tp}}$ its vertical velocity. The normal contact force is defined as

$$F_{\mathrm{n,tip}} = \begin{cases} 0, & Y_{\mathrm{Tp}} > 0, \\ \max\Big(0, -k_y Y_{\mathrm{Tp}} - c_y \dot{Y}_{\mathrm{Tp}}\Big), & Y_{\mathrm{Tp}} \le 0, \end{cases} \tag{43}$$

where k_y and c_y are the vertical contact stiffness and damping coefficients, respectively. This formulation allows the pole tip to detach naturally from the ground when no contact is present.

Tangential interaction between the pole tip and the ground is modeled using a Coulomb friction law. The friction force magnitude is proportional to the normal force,

$$F_{\mathrm{t,tip}} = \mu F_{\mathrm{n,tip}}, \tag{44}$$

where μ is the friction coefficient. To ensure that the friction force always opposes the direction of motion, the sign of the tangential force is determined from the horizontal velocity of the contact point.

The resulting contact force acting at the pole tip is then

$$\mathbf{F}_{\mathrm{tip}} = -\,F_{\mathrm{t,tip}}\,\mathrm{sign}(v_x)\,\mathbf{e}_x + F_{\mathrm{n,tip}}\,\mathbf{e}_y. \tag{45}$$

This force-based formulation removes the artificial backward pulling effect observed with the holonomic constraint and allows the pole tip to transition naturally between sticking, slipping, and detachment phases during propulsion.

While this approach increases model complexity and introduces additional parameters that must be identified, it provides a more physically realistic representation of pole–ground interaction and yields smoother forward dynamics, making it more suitable for optimization studies of pole length and seat height.

4 Conclusions & Recommendations

Optimal Spike Sit-ski technique

Trunk engagement and Core Activation Athletes with greater trunk control should actively engage their core muscles during poling. Importantly, a larger trunk flexion-extension range is linked to better performance as trunk flexion ROM correlates significantly with higher propulsive impulse and velocity (5), (19), (7). Besides, using trunk drive more allows for improving fatigue in double poling as it distributes effort across larger muscle groups, reducing over-reliance on the arms.

Pole plant position and angle: Use a forward pole plant with an optimal angle. Planting the poles further ahead of the sit-ski (i.e. with a more horizontal lean) allows a longer push and delays the peak force to later in the stroke, when the poles are tilted optimally for forward thrust. In contrast, an overly vertical pole plant shortens the poling time and reduces impulse (13) (14).

Timing and Cycle Phase Distribution: Adapt the poling cycle to the terrain by adjusting timing. Improve efficiency uphill by adopting a longer poling phase and shortening the recovery phase. This higher duty cycle (fraction of time spent poling) allows for more work per stroke. In contrast, a quicker cycle with shorter strokes is more effective on flat terrain.

Rapid Force Development: Focus on reaching the peak pole forces quickly and smoothly after pole plant. The initial impact force at pole plant followed by a rapid force buildup can stiffen the body and engage muscles for a powerful thrust (13). Research shows that as poling frequency and speed increase, the time to peak force decreases and an initial impact force becomes more pronounced. Training should therefore emphasize developing an explosive poling action.

Symmetry and Balance: Strive for symmetric force application on both poles. Asymmetries in technique can cause energy losses and uneven loading on the body (16).

Build endurance: User research shows that regular riding appear to improve endurance and comfort. Riding regularly will help the user in ride longer with less fatigue.

Spike Configuration & Design Recommendations

Personalized set-up: Research highlights that a personalized sit-ski setup is essential for performance and comfort. In particular, seat height and pole length are key adjustable parameters. Increasing seat height and/or pole length can improve the effective leverage (moment arm) and make force production more efficient, but these changes may also influence the skier's balance and stability, potentially increasing the risk of instability if not matched to the user's capabilities. One suggestion could be that the seat could be springloaded or have multiple preset heights that can be selected based on the user's skill and comfort. This adjustability ensures that the design serves beginners (who need more stability) and advanced athletes (who may exploit a higher position for performance).

Adjustable Trunk support and stability aids

- **Promoting trunk movement vs. stabilization.** Both the literature and the user survey highlight the importance of trunk and core contribution for efficient sit-ski propulsion. However, not all users have sufficient trunk control, and many may require external support to achieve effective posture and force transfer. A potential design improvement is therefore to enable or "mimic" trunk contribution through integrated support or assistive mechanisms (like a springloaded system). Importantly, any solution must be designed so that it does not compromise stability, meaning trunk support and overall seat stability should be developed coherently as one system.
- **Configurable trunk supports.** Trunk support should be adjustable to provide stability without unnecessarily restricting movement. Both literature and user feedback indicate that many users retain partial core control, but still benefit from additional stabilization. The support design should encourage a controlled forward lean

(to facilitate propulsion) while limiting excessive backward lean, which may reduce efficiency and increase perceived instability.

- **Reducing energy loss and fatigue.** Optimizing support systems is particularly important because instability and compensatory movements can cause energy leakage, contributing to higher effort and fatigue. This is especially relevant during longer rides, where fatigue accumulates and the ability to stabilize posture declines. Well-designed trunk supports may therefore improve propulsion efficiency, reduce upper-limb overuse, and enhance comfort over time.

Pole Interface and Angle Guidance: Although ski poles are separate equipment, the sit-ski design can indirectly influence pole usage. The Spike should ensure that nothing in the frame obstructs the natural poling motion. For example, the athlete's hands and the pole tips should be able to move freely at the start and end of the stroke without hitting the sled or seat. Consider the typical pole angle range: athletes with strong trunk control often use longer poles and a more forward pole plant, whereas those with less trunk stability might prefer a slightly shorter pole to maintain control. While the sit-ski cannot change the poles, it can provide mounting points or reference markers to assist with pole positioning as well. One idea is to have adjustable "pole guides" on the frame that help the skier consistently plant the poles at a certain location or angle relative to the ski.

Model conclusions & Recommendations

While the present model formulation does not yet enable robust predictive optimization of sit-ski configuration, it can still serve as a valuable design-exploration and decision-support tool for SmartGroup. The model enables systematic What-if studies, where changes in sit-ski configuration (e.g., seat height, sit-ski length, and pole length) and design modifications (e.g., an added spring mechanism) can be implemented and their effects observed through the resulting kinematics, joint torques, and contact forces.

This use case must, however, be interpreted within the current limitations of the model. The model represents a single pole stroke, is restricted to a planar (2D) formulation, and relies on simplified assumptions regarding contact and user-specific biomechanics.

The following developments are recommended to improve both model fidelity and its usefulness for SmartGroup:

- **Replace the holonomic pole-tip constraint with a force-based contact model.** Implementing a collision/penalty-based contact formulation (normal compliance + friction) would allow the pole tip to naturally stick, slip, and detach. This would remove the non-physical backward pulling observed with the current constraint and enable more realistic propulsion dynamics. With this improvement, an optimization objective such as maximizing traveled distance (reach) for a given effort becomes feasible.

- **Extend the simulation from one stroke to multiple consecutive strokes.** Simulating repeated pole plants would better represent endurance sit-skiing and allow analysis of cumulative fatigue indicators, stroke-to-stroke consistency, and stability over time.

- **Formulate the problem as an optimal control problem using stronger optimization tools (e.g., CasADi).** Instead of optimizing a limited set of parameters for a fixed torque pattern, an optimal control formulation would allow the torque profiles to be optimized directly under dynamic constraints. This generally improves convergence and allows the inclusion of task constraints (e.g., pole planting conditions, stroke timing, stability constraints).

- **Calibrate and validate model parameters using motion experiments.** Collecting kinematic data (joint angles, trunk motion) and, if possible, pole forces would allow tuning of contact parameters (stiffness, damping, friction) and improve model accuracy.

- **Extend to a 3D formulation once the 2D model is validated.** A 3D model would enable investigation of asymmetric propulsion, lateral stability, and steering effects, which are relevant for real sit-skiing conditions.

5 Appendix 1

Table 2: Appendix: Literature Review overview

Study	Purpose	Sample Group	Method	Results
(5)	Investigate the muscle activation strategies in athletes of different impairment levels in sit skiing. Define an improved methodology for the classification of the impairment level and sit-ski position.	DP sit-skiing	Literature review, EMG measurements	Rectus abdominalis activity is higher in LW12 athletes compared to LW10 Erector spinae activity is higher in the kneeled position. Proposed new classification procedure based on reflex activity of the m. rectus abdominis after forward and backward perturbations.
(19)	Explore which muscles are important which sit ski athletes use in different sitting positions based on their disability	DP sit-skiing / 10 health male XC skiers	Ergometer test, EMG measurement. 75% of maximum performed in each position, unforeseen forward and backward perturbations to test balance.	Kneeled position achieved the highest velocity at the ergometer and had higher EMG levels (triceps, trunk, hip and thigh muscles). No difference in upper body acceleration between sitting conditions for the perturbations.This shows that this could be a good test set up, independent from the sitting position
(6)	Analyze the biomechanics of elite XC sit-skiing athletes during field competition	Competition DP sit-skiing (1K sprint) / 35 men and 15 women paralympic athletes	Markerless motion tracking during field competition. 2D kinematics analysis.	Proposal to divide the poling in 3 phases: Poling (PP) , Transition (TP) and recovery phase (RP). PP starts with max body and arm extension. A decrease in elbow angle in the first part of PP and then increase towards the end of PP (extending). The sledge has initial acceleration due to propulsive inertial effect of the abrupt arm lowering (not effective pole plant) Trunk oscillation is observed to be maximum at the end of PP and minimum in the middle of RP. ROM of the trunk is bigger for LW11 and LW12 mono-lateral amputees when compared to LW10 and LW12 bilateral amputees. ROM of the trunk is important for effective pushing. The presence of abdominal muscles is effective for force generation and shows a big difference between athletes that have no functional abdominals or extensors and the other group. straps and curled-up legs limit the trunk flexion.
(10)	Analyse the pole force and effectiveness for XC skiers at different inclination grades (from 2 to 8 degrees)	XC Elite standup skiing / 12 experienced female athletes	VO2max measurements, treadmill, diagonal stride. Pole force (load cell) and pole motion (Qualisys) measurement	Increased inclination leads to increased pole force, change in timing parameters (longer pole plant and lower recovery time, higher duty cycle) and an increase of tangential component of the pole force. Increase in power output required to ski at steeper slopes for overcoming gravity was mainly done by a greater power generation through the pole but also an increase in tangential component of the force. Increase of duty cycle also increases the active phase in a higher grade, a higher proportion of the cycling time is used for generation propulsion force.

Continued on next page

Study	Purpose	Sample Group	Method	Results
(9)	Determine whether different sitting positions affect performance while skiing	Paralympic XC sit ski / 10 male elite athletes (LW10=2, LW10.5=0, LW11=1, LW11.5=4, LW12=3)	Maximal speed test, K-means cluster analysis for natural grouping.	the cluster algorithm grouped athletes into two clusters based on the similarity of performance data: Groups matched closely with the sitting position max speed and force was most important factor separating the groups (PCA) Higher level of force and speed found in the kneeled position. Which might be due to greater trunk movements and better ability to stabilize the core against the pole reaction.
(12)	Analyze how poling camber angle affects the capacity of power output and influences biomechanical parameters of the DP sitskiing	XC sit skiing / 24 abled body students (non athlete)	Motion capture measurement, pole force measurement, muscle activation with EMG measurement	With increasing camber angle, CT is increased, PT is decreased, Cycling distance is increased, output power is increased. But efficiency is decreased! Ant Delt, and Biceps are sensitive to poling camber angle Poling angle increases elbow and trunk ROM, making strokes longer and faster This requires a greater extension effort at the shoulder (due to increased moment arm), but it directs the pole force forward, improving propulsion efficiency and power output
(15)	Analyze the kinematics of the shoulder, elbow and wrist in experienced cross country sit skier	XC sit+skiing/ 1 experience XC sit-skier	Motion Capture system on treadmill (Qualisys), 6 camera set up, Musculoskeletal uppoer body model	The demand for range of motion in shoulder and elbow is not large when cross-country sit skiing as long as the sit ski poler is able to control the movement of his trunk and is in balance sitting.
(13)	To further the understanding of double poling (DP) through biomechanical analysis of upper and lower body movements during DP in cross-country (XC) skiing at racing speed (85% of Vmax)	Elite XC skiers / 11 athletes	Treadmill measurement, kinetic, kinematic and EMG measures at 85% of the individually calculated Vmax. Kinematics measured with gonio meters and video measurement	There is an initial impact force peak and an active force peak (PPF) in pole plant, followed closely after each other where the PPF is the highest. The force peaks positively correlate to the velocity at 85% of Vmax during DP There is an active flexion-extension pattern of; elbow, hip, knee, and ankle joints with minima occurring at PPF. Flexion of the hip is negatively correlated with the minimum angle of the elbow and poling time: more bending of the hip (forward lean) allows for more bent elbows at poling and a longer push off time of the pole (lower and upper body strategies are coupled). Better skiers (strategy A) have; higher angular elbow and hip-flexion velocity, smaller minimum elbow,hip and knee angle (more flexion), higher pole force and shorter poling phase. During the first half of the poling phase, muscles are activated sequentially in a proximal-to-distal order (see muscle analysis) There was significant EMG activity in lower body muscles, again showing the contribution of lower body work

Continued on next page

Study	Purpose	Sample Group	Method	Results
(8)	Explore how different levels of impairment have an effect on sit-ski performance in competitions	Elite XC sit ski/ 46 athletes	video based observation during competition track using Kinovea software	trunk movement increased notably in classification level (LWX) in both sagittal and frontal plane. Poling frequency decreased on flat parts and increased uphill. The sitting position is an important factor in improving the poling technique.
(11)	Compare the work rate and associated physiological and biomechanical performance determining variables between flat and uphill cross-country sit-skiing	XC sit ski / 15 able-bodied male XC skiers	treadmill test: submaximal stages with increasing speed, followed by test to exhaustion and verification test. measuring respiratory variables, HR, Motion capturing cameras.	The peak work rate was 35% higher in uphill scenario when compared to flat. this coincides with a higher Work per cycle the poling time was also twice as long No difference between VO2peak, RPE or any of the peak physiological variables was found So the cardiovascular system was taxed equally and no difference in exhaustion Gross efficiency was higher in uphill, with lower physiological strain and perceived exertion at the same WR compared to flat. This suggests technique is easier to maintain uphill, while flat skiing requires more metabolic energy to increase WR. Sit-skiers achieve higher WR and better efficiency uphill, making it advantageous to increase effort on climbs. Uphill skiing allowed longer PT and shorter swing times, letting muscles work in a more favorable range of the force-velocity relationship, likely explaining the efficiency advantage.
(7)	Explore the force generation profile in relationship with the role of the trunk in double poling sit skiing	Elite XC sit skiing / 12 male athletes (LW10-12)	Flat snow terrain at submaximal speeds (73%). 2D video capture and pole force analysis.	At equal axial pole force, LW10-11.5 athletes lost between 21-4% of propulsive force vs LW12, due to trunk geometrics and differences in pole angle. LW10-11 show trunk extension/ position maintenance LW11.5-12 show strong flexion of the trunk combined with smaller pole angles. They could produce larger propulsive forces and therefore greater cycle lengths at lower cycle rates at the same speed. Maximum speed increases from LW10-12 and is significantly correlated to trunk flexion ROM. The Trunk flexion ROM showed a significant relationship to the impulse of propulsive force and pole angle to the ground.

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Study	Purpose	Sample Group	Method	Results
(16)	Understand how seating configurations (changing the kneeled seat angle) affects elite sit-ski athletes	Elite XC sit skiing / 4 athletes (3 Female)	Capturing loads on different parts of the sit ski using load/pressure sensors. Capturing data for different seating configurations (seat angle and raising knee rest)	The load on the knees is highly individual, where a 60 degrees angle with flat knees was the highest Asymmetry was most distinct at the start of the movement cycle and in uphill skiing (demands are greater here). High belt forces were observed for athletes with more forward lean / core driven technique This force sensor could be used to determine the LW-classification The study showed that customization of equipment is essential.
(14)	Analyze the hypothesis whether the horizontal pole force is more predictive for maximal skiing speed that the resultant pole force.	Elite XC stand up skiing / 16 athletes	Treadmill, maximum speed test. Motion capture and pole force measurements	Overall: High-level performance in double poling comes from combining high pole force capacity with optimal timing and positioning. For faster performance: Peak force occurs later in the poling phase when pole angle allows for more propulsion. faster skiers are able to generate higher peak pole forces while slower skiers rely more on impact Higher impact forces were negatively related to speed More inclined pole angles at pole plant reduce efficiency. Because of shorter distance covered (pole is planted closer to body), shorter poling time, lower impulse. Faster skiers cover more forward distance with their poles, allowing longer poling times and cycle lengths. More vertical pole plant and forward body lean support longer force application.

Continued on next page

Study	Purpose	Sample Group	Method	Results
(?)	Interview with Viljar to gain more knowledge on the limitations and challenges in sits skiing	XC Sit-ski expert	Interview	A lot of energy gets lost when the straps are not tightened ->propulsion goes into balancing movement (= energy loss). On seated sitski: more backwards lean for an extended period of time, slowing people down Especially people with less core function have this issue. People with more core function have shorter poles ->use upper body to put weight on poles People with less core stability have longer poles ->longer momentum angle pole timing and cycle duration is the most important measure for performance A higher seat is better for momentum but less good for stability Fatigue is the biggest problem in beginner users Focus on general use, in competition people change their set up anyways. Most sit skis have been designed within the rules of competition, it is not beginner friendly. 90-99% is not competing Focus on seated to approach more users (70%) Depending on the disability it is difficult to determine when someone needs a seat ski versus a kneeled. Stability vs Hip freedom is the trait off in better sit ski design

6 Appendix 2

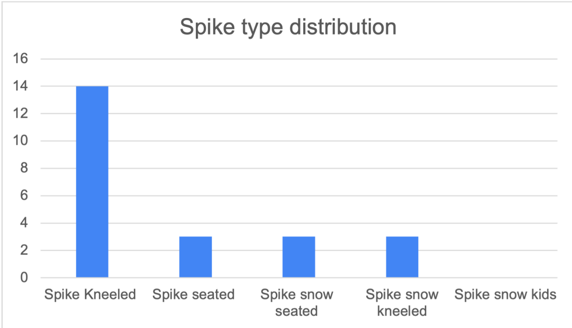

Figure 7: Spike Type Distribution

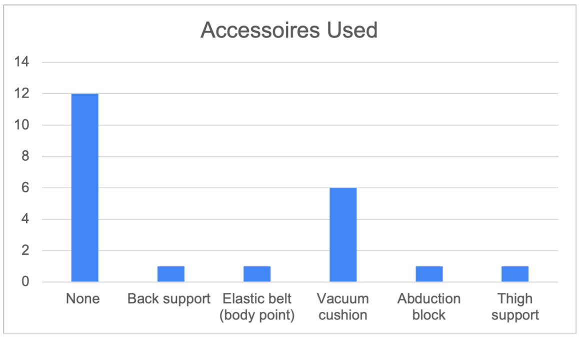

Figure 8: Spike Accessoires

Figure 9: Spike goal

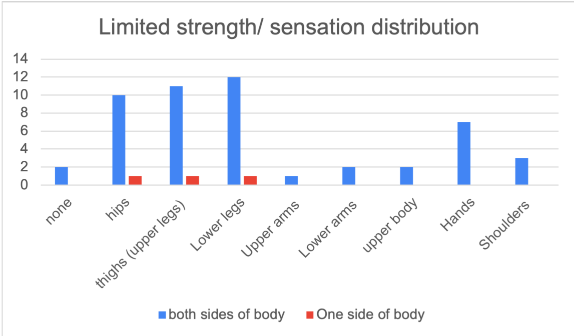

Figure 10: strengt and sensation limitations

Figure 11: Trunk control

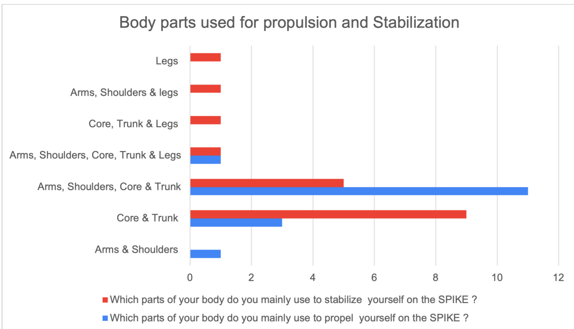

Figure 12: Propulsion and Balance

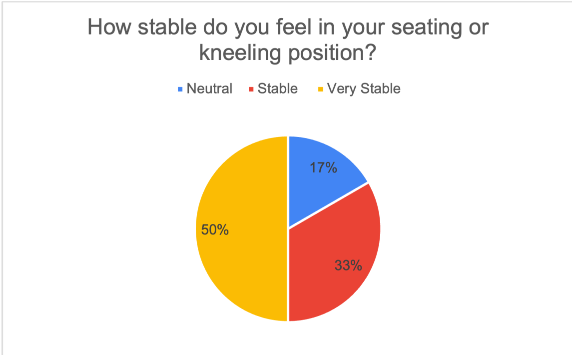

Figure 13: Stability

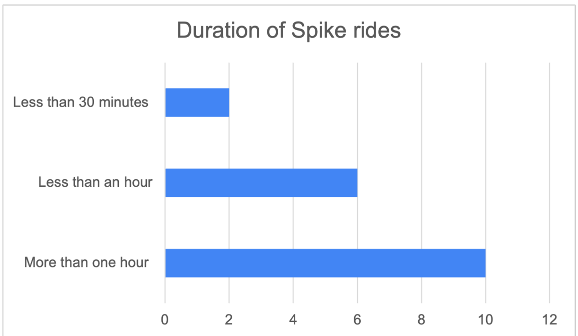

Figure 14: Spike duration

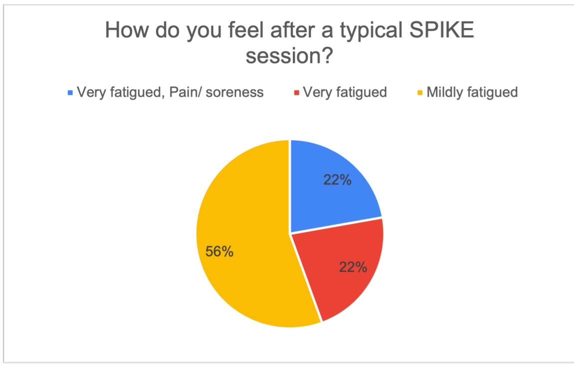

Figure 15: Fatigue

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