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Ergonomic design of rock-climbing clothing: beyond static anthropometry to movement-informed design

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ABSTRACT

Conventional garment design typically relies on static anthropometric measurements, which may not adequately account for changes in body dimensions and posture during highly dynamic activities such as rock climbing. This study investigates how climbing-specific movement analysis and dynamic anthropometry can inform ergonomic design of rock-climbing clothing. It combines a review of relevant research with observational and movement analysis of climbers using the Xsens motion-capture system to examine relationships between dynamic body dimensions and garment pattern requirements. The analysis identified changes in body dimensions during climbing and highlighted the crotch and inner-leg, knee, upper-back, armhole and sleeve regions as key areas for pattern development. The findings demonstrate the limitations of static anthropometry for dynamic garment design and indicate areas where pattern adaptations and ease require consideration. The study provides a basis for developing climbing-specific pattern-engineering strategies. Further prototype testing is required to validate specific modifications and ease allowances.

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KEYWORDS
Rock-climbing clothing; garment design; pattern making; motion analysis; motion capture

1. Introduction

Rock-climbing is an increasingly popular physical activity and a competitive sport worldwide. At the same time, it is a physiologically and psychologically demanding activity that is influenced by many external environmental factors. Ergonomic and functional rock-climbing clothing plays a crucial role in ensuring the safe completion of routes during activities like ice-climbing, mountaineering, traditional climbing, and other forms of climbing in mountainous areas exposed to adverse weather conditions such as high winds, heavy rains or snowfalls, and low temperatures. It is essential to prioritise appropriate climbing attire alongside proper climbing techniques and the use of specialised equipment. In designing such clothing, a primary concern is the movement of a climber, as ergonomic and functional rock-climbing clothing should not hinder or restrict the climber from performing their climbing activities. However, existing literature lacks published standards and defined criteria for the apparel requirements specific to rock climbers, and research in this field remains limited. Additionally, the current range of outdoor clothing fails to adequately address the needs of rock climbers, primarily due to the absence of comprehensive data on the specific requirements and fundamental principles unique to the sport of rock climbing (Novikova, 2025; Novikova, Joseph, & Cleveland, 2023).

Outdoor climbing introduces distinct challenges that differ from indoor climbing, including heightened anxiety associated with lead climbing, environmental factors such as weather and conditions, as well as the importance of familiarity with specific rock types and angles of inclination (Ezzy, Hagstrom, Shorter, & Gray, 2018). When it comes to professional clothing, the design of such products should be guided by the dynamics of daily activities (Neves, das Brigatto, & Paschoarelli, 2015). Factors such as the external environment, biomechanical performance, task characteristics, and the user's anthropometric features play a vital role in providing valuable information necessary for enhancing the effectiveness of clothing during professional exercises (Neves et al., 2015). The development of ergonomic apparel design that caters to the diverse needs of climbers must take into account the relationship between clothing and user (Johnston & Koo, 2017; Michaelson, Teel, & Chattaraman, 2018; Novikova, 2025; Novikova et al., 2023) This includes

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considering anthropometric parameters and specific movements of climbers that may be influenced by clothing as well as environmental factors such as weather and conditions.

In pattern engineering, garment patterns are developed using individual or standard body measurements, ease allowances, and established pattern-making techniques. Anthropometric dimensions can be classified as static (or structural), referring to measurements of the body at rest; dynamic, referring to dimensional changes associated with movement of individual body parts; and functional, referring to measurements associated with coordinated movements involving multiple parts of the body. The collection of anthropometric data requires clearly defined measurements and anatomical reference points, appropriate measurement methods, representative samples, and suitable statistical analysis (Júlio Padez, Gonçalo Coelho Costa Pombo, Manuel Garcia dos Santos, & Madalena Rocha Pereira, 2020; Neves et al., 2015).

In garment design, these measurements must also be considered in relation to ease, the additional space incorporated into a garment to accommodate fit, comfort, mobility and intended design effects (Gill, 2011). This is particularly important for garments designed for highly dynamic activities, where body dimensions and spatial relationships can change substantially during movement. Pattern-engineering techniques can therefore be used to translate anthropometric and movement data into garment patterns that respond to functional and ergonomic requirements (Anand, 2011).

This paper presents a review of current research into the anthropometric measurement of rock climbers to support the development of ergonomic rock-climbing clothing. It also examines methods used to observe climbers and measure their body dimensions. More specifically, the research focuses on the observation and analysis of climbers' body movements during climbing using the Xsens system. This technology uses a series of interconnected Inertial Measurement Units (IMUs), together with biomechanical models and sensor-fusion algorithms, to capture body movement (XSens, n.d.). The resulting movement data are analysed to identify changes in body dimensions during climbing and interpreted in relation to specific garment pattern areas and potential construction responses, providing a basis for movement-informed pattern-engineering strategies for ergonomic rock-climbing clothing.

2. Literature review

This review encompasses a comprehensive analysis of scientific publications, including peer-reviewed journal articles, conference proceedings, theses, webpages and standards, with the aim of examining information pertaining to anthropometric measurements of athletes in both static and dynamic contexts. It also explores the methods employed for observing climbers and capturing body measurements, as well as the utilisation of these parameters in the development of ergonomic sports clothing. It should be noted that the number of studies available in this particular domain is limited. Existing research has primarily focused on investigating anthropometry, strength, endurance and flexibility variables among rock climbers and establishing correlations with climbing performance indices (Ezzy et al., 2018; Grant, Hynes, Whittaker, & Aitchison, 1996; Magiera & Roczniok, 2013; Mermier, 2000; Sheel, 2004). For example, Ezzy et al. (2018) conducted a study to explore the anthropometric and physiological measures, specific training approaches, and climbing experience in relation to volume components that may serve as predictors of outdoor climbing performance.

The literature includes studies that have analysed climbing postures and motions to simulate climbing behaviour using motion capture technologies (Cha et al., 2015; Richter, Beltrán, Köstermeyer, & Heinkel, 2020). Although these studies are not directly related to the development of rock-climbing clothing, they provide valuable insights into the application of motion capture technologies. For instance, Cha et al. (2015) examined postures and movements in sport climbing using Microsoft Kinect for the generation of realistic 3D climbing animations. Richter et al. (2020) have provided a comprehensive overview of available technologies, algorithms and unresolved questions in the field of climbing motion analysis.

Climbing poses unique physiological demands, necessitating sustained and intermittent isometric contractions of the forearm muscles for upward propulsion (Sheel, 2004). The range of motion involved in climbing encompasses knee and shoulder extension, knee flexion, grip and finger strength, bent arm hang, grip endurance, hip and shoulder flexibility among others. Therefore, physical and anthropometric characteristics of climbers such as arm length, leg length, arm span/height, and joint angles should be measured and compared in both static and dynamic contexts. These measurements should be duly considered in the technical design of rock-climbing clothing to ensure optimal fit, ergonomics and functionality.

The literature also discusses the analysis and development of ergonomic clothing that takes into account the anthropometric measurements, postures and movements of athletes in dynamic settings, with a specific focus on the requirements of the sport. Several papers

have explored these aspects (Choi & Kyung, 2018; Jeong, 2008; Viziteu & Curteza, 2021; Viziteu, Curteza, & Avadanei, 2021). For example, Jeong (2008) investigated the relationship between the construction of a skate pants pattern and clothing fit aiming to enhance comfort during the full range of athletes' movements and postures. Choi and Kyung (2018) examined the differences in construction between high-performance jackets worn by professional climbers in extreme environments, and jackets suitable for daily wear. Their findings highlighted diverse and complex aspects of construction as well as the stretchability, water resistance, and venting system required based on the performance level of outdoor jackets. Viziteu et al. (2021) aimed to establish a framework of ergonomic knowledge in the fashion engineering and design process, particularly focused on functional clothing for boulder athletes. Their research emphasised the importance of incorporating ergonomic principles into clothing design. Furthermore, Viziteu and Curteza (2021) explored the applicability of computerised 3D virtual clothing simulation programmes in developing patterns for men's rock-climbing pants.

Collectively, these studies have contributed to the understanding of anthropometric consideration, movement analysis, and ergonomic design principles for rock-climbing clothing, addressing the specific needs, demands, and challenges faced by climbers. However, the review of existing literature identifies that there is limited research focussed specifically on the anthropometric measurements and ergonomic design considerations for rock-climbing clothing. This indicates a research gap that necessitates further investigation to address the specific needs and challenges faced by climbers. In light of this knowledge gap, we conducted a survey and observational study to gather primary data and gain insights into the anthropometric characteristics, movement patterns, and ergonomic requirements of rock climbers to inform pattern engineering.

3. Methods

The research methodology employed in this study followed a systematic, user-centred design approach, informed by the designs of previous studies (Cherrington et al., 2020; Naesgaard, Storholmen, Wiggen, & Reitan, 2017; Putnam et al., 2016). It drew from the findings of earlier research (Novikova, 2025; Novikova et al., 2023) which involved a survey of rock climbers' clothing experiences and preferences, and a structural and material analysis of commercially available clothing used by climbers. Employing mixed qualitative and quantitative methods, the current study aimed to provide a deeper understanding of the context and the underlying problems to improve the ergonomic design of rock-climbing clothing and inform the development of design solutions to address these issues. A fundamental aspect of the research is the adoption of a 'people-centred' approach, which emphasises active engagement with 'critical end-users' (McCann & Bryson, 2009). By involving rock-climbers from the earliest stages of design development, the study seeks to gain insights into their existing experiences and needs. This 'people-centred' approach enables designers to create solutions that align closely with user requirements, enhancing the overall effectiveness and useability of the final product or service (McCann & Bryson, 2009). The design and development process of functional and ergonomic rock-climbing clothing must be approached within the context of the intricate interaction among the components of a simplified system, namely the climber, clothing and climbing conditions (see Figure 1).

The model below (Figure 2) illustrates the relationship between these elements, highlighting their dynamic nature and the various factors that influence their interactions. This model captures the different aspects of the system, including dynamic postures and movements of the climber, dynamic parameters of the climbing conditions, and the dynamic ease required for optimal performance. These dynamic components play a significant role in informing the pattern engineering solutions for specific parts of the clothing, as the clothing design must accommodate and enhance the climber's movements and functionality. This comprehensive approach ensures that the clothing not only provides comfort and protection but also supports the climber's range of motion and facilitates optimal performance during dynamic climbing activities.

3.1. The survey

The survey component of the study utilised qualitative methods in the form of a questionnaire to gain a deeper understanding of the climbers' experiences, issues, and preferences related to clothing. The questionnaire, titled 'Rock climber's clothes – satisfaction, preferences, requests and needs of rock-climbers', was administered online using the Qualtrix platform (https://www.qualtrics.com/). Key findings that informed the current research included the identification of a range of rock-climbing postures and techniques by the respondents. Further information about the survey can be found in an earlier publication . The questionnaire, titled 'Rock climber's clothes – satisfaction, preferences, requests and needs of rock-climbers', was administered online using the Qualtrix platform (https://www.qualtrics.

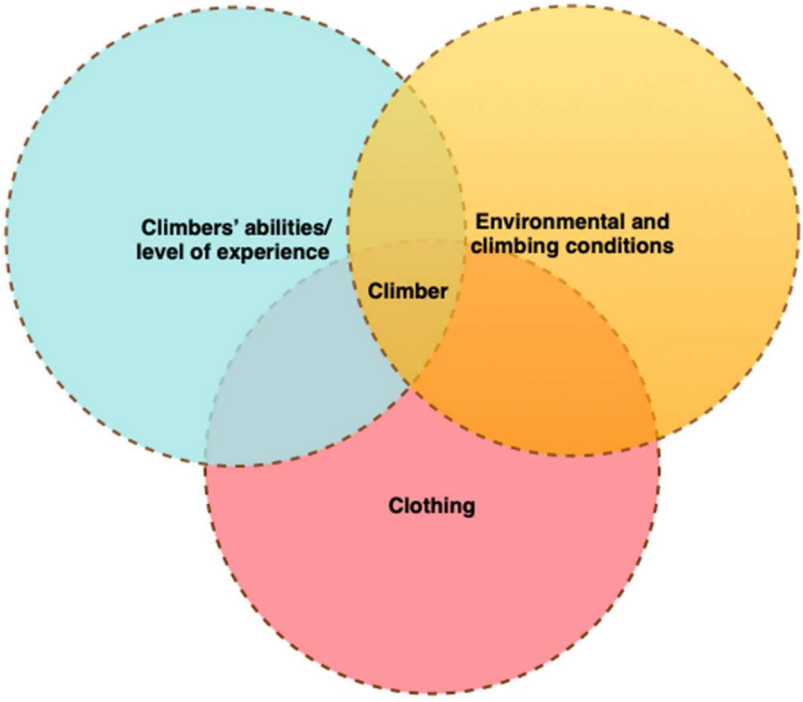


Figure 1. The interaction among the climber, clothing and climbing conditions system.

com/). Key findings that informed the current research included the identification of a range of rock-climbing postures and techniques by the respondents. Further information about the survey can be found in an earlier publication (Novikova, 2025; Novikova et al., 2023).

3.2. The observation

To facilitate the observation phase, two experienced climbers were recruited to participate. The observation took place on an indoor climbing wall at the Sports Performance Research Institute New Zealand (SPRINZ), located in Auckland University of Technology's Millennium gym. The climbers worked together, with one engaged in climbing while the other served as the belayer, simulating real rock-climbing scenarios. During the observation, one of the climbers wore the Xsens system, specifically the MVN Awinda Straps System (XSens, n.d.). The system included 18 Wireless Motion Trackers (MTw), an Awinda Station, two Awinda

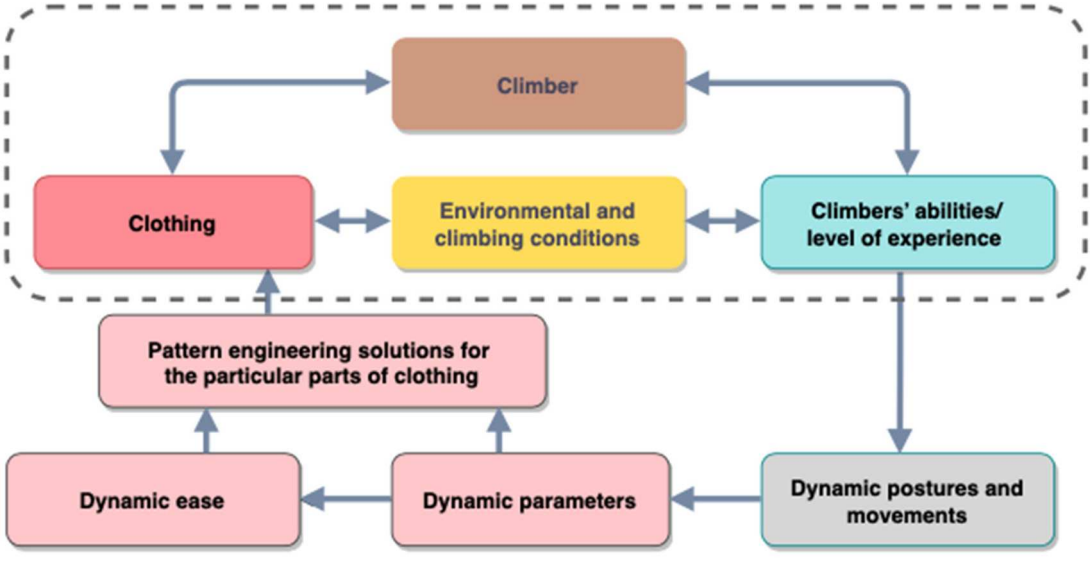


Figure 2. Model of the relationship between components of the climber, clothing and climbing conditions system.

Chargers, MTw full body Velcro straps, including shirts, headbands, footpads, gloves, a Segmometer, and a Quick Setup sheet. Each MTw unit contained 3D linear accelerometers, 3D rate gyroscopes, 3D magnetometers, a barometer, and an internal battery. These trackers were strategically placed on the body segments, secured by straps, to measure the motion of each body segment (Figure 3). Figure 4 shows the Wireless Motion Trackers of the MVN Awinda system, highlighting the components used in the observation session.

Proper placement and secure fastening of the motion trackers are essential for accurate motion capture and minimising skin-motion artefacts (Xsens Technologies B.V., 2020). Each tracker has a specific ID used throughout the recording process. The MVN Straps provided secure attachment during most movements, while the MVN Analyze/Animate software enabled real-time monitoring and recording (Xsens Technologies B.V., 2020).

The setup workflow stage encompasses three key components: subject body dimensions, data fusion, and sensor-to-segment calibration. Prior to sensor-to-segment calibration, the subject's body height and foot length (shoe length at the time of the measurement) need to be inputted into MVN Analyze/Animate. These measurements enable the software to calculate other segment lengths based on an anthropometric model. Segment calibration is a crucial step that aligns the motion trackers with the segments of the subject. Once the calibration data has been processed, the system provides an indication of the quality of estimated calibration parameters and displays warnings if any issues are detected. The subsequent stages involve the Preview and Recording sessions.

During the recording session, data was collected according to an observation protocol. The climber's dynamic parameters were measured and their movements were observed and analysed during a range of rock-climbing postures and techniques defined by experienced climbers in the earlier survey (Novikova et al., 2023). The recording sessions consisted of three parts:

(1) The climber performed commonly used climbing movements at a low altitude or while remaining on the ground
(2) The climber demonstrated a range of movements, postures and techniques while climbing upwards, including high stepping and mantle technique, lie-back, stemming technique, etc. (Figure 5)
(3) The climber performed a chimney climb.

The MVN Fusion Engine performs calculations to determine the position, orientation, and other kinematic data of each body segment relative to an earth-fixed reference coordinate system. The body frames are initially aligned with the Global reference frame when the subject assumes a T-pose. For the calculation of joint angles, an additional frame of reference based on a standard anatomical pose is utilised to define the body frames. The origins of the joints are determined by the anatomical frame and are defined in the centred of the functional axes, with the X, Y and Z directions aligned with functional movements (Schepers, Giuberti, & Bellusci, 2018; Xsens Technologies B.V., 2020). Once the recording is completed, the data can be imported to the computer by connecting the Body Pack. The final stage of the workflow involves data analysis, where the collected data is analysed and interpreted.

During the observation session, multiple sources of data were collected, including the primary data obtained using the Xsens system technology, as well as photographic and video recordings, and manual measurements. Manual body dimensions were taken using a tape measure according to ISO 8559:1989 (en) Garment construction and anthropometric surveys – Body dimensions (International Organization for Standardization, 1989). In addition, the placement and interaction of equipment such as harnesses and ropes with the clothing were assessed and recorded during the observation session. These measurements and assessments will be taken into consideration during the pattern making stage to inform the ergonomic design of rock-climbing clothing. For dimensional comparison, the static measurement was used as the baseline and the percentage change in each selected posture was calculated. The values are descriptive for the observed participants and postures.

4. Results

In co-relating the various data sources, the first step involved synchronising the MVN recording with photo and video data. This synchronisation process was crucial for gaining a better understanding of the biokinetics involved in the climbing process and identifying the relevant parameters for evaluation. Manual correction was performed to address any time discrepancies between the MVN data and video recordings.

The MVN Analyze/Animate application provided various viewing options, including the 3D character in the 3D viewport and orthogonal views. To ensure consistency, a similar viewpoint to that in the photo or video screenshots was used for analysis (see Figure 6). In addition, the video and screenshots incorporated

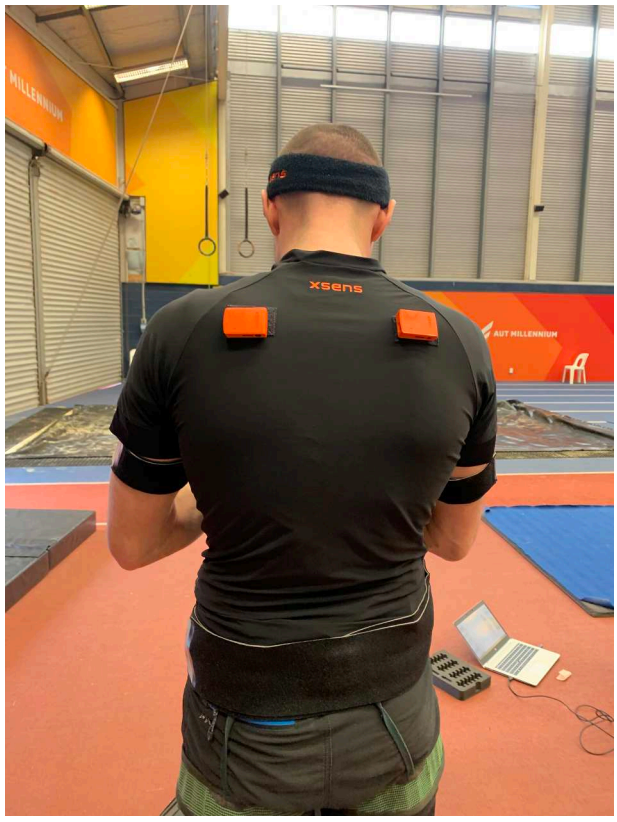


Figure 3. The placement of Shoulder Motion Trackers on the Scapula (shoulder blades).

graphical representations of the kinematic data obtained from the MVN system. Figure 6 shows an example of the synchronisation process between the MVN data and photos, highlighting the integration of multiple data sources for comprehensive analysis.

The data obtained from the observation sessions was exported to an Excel spreadsheet for further analysis. The spreadsheet contains comprehensive information about each session, including general session details, kinematic data for each body segment, joint angle parameters, and their corresponding positions and orientations. This dataset includes various metrics such as velocity, acceleration, centre of mass, rotation, and more.

These terms highlight the dynamic nature of stretching or movement and how it affects the body dimensions or measurements relevant to the design of rock-climbing clothing. Thus, from the MVN data of dynamic range of motion, recorded during the observation sessions for the purpose of clothing development, the focus was placed on analysing the angular parameters of the hip, knee, shoulder, and elbow joints measured in degrees. The hip, knee and shoulder joints allow for rotation in three directions: flexion(+)/extension(-), abduction(+)/adduction(-), and internal(+)/external(-) rotation (Zhang, 2021). Table 1 presents the maximum and minimum values of each angular parameter recorded across the three observation sessions. This Table provides a summary of the joint angle parameters observed during the climbing sessions, offering insights into the range of motion and variability of the selected joint angles.

The table demonstrates that the climber exhibited a high range of motion during climbing. Overall, flexion

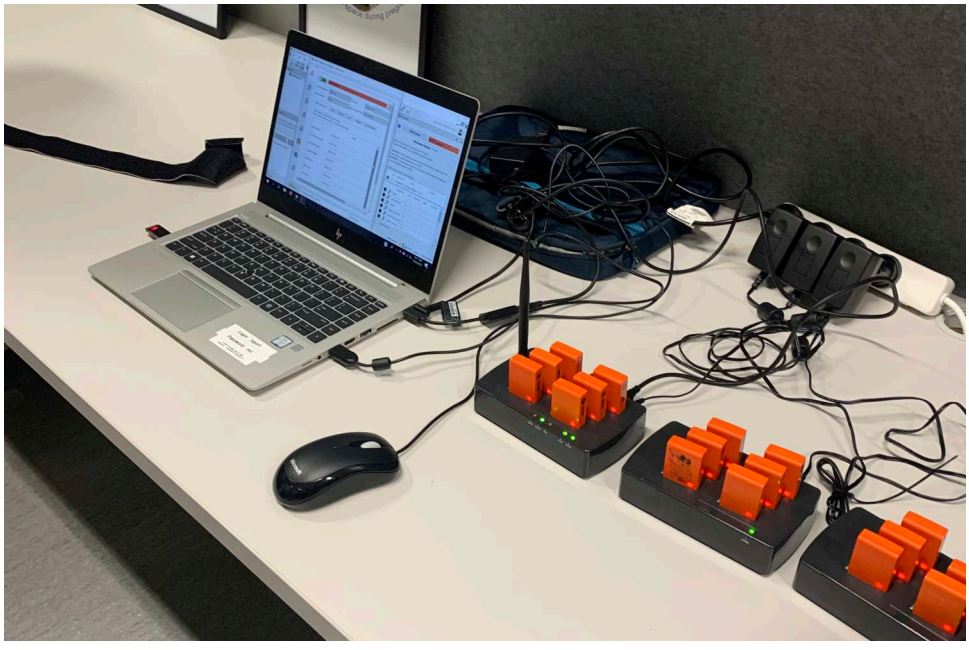


Figure 4. Identifying the Wireless Motion Trackers of the MVN Awinda system, prior to placement on the body.



Figure 5. Example of some commonly used postures in rock-climbing.

showed the maximum parameters for the presented flexible joints. Flexion of the hip, for example, involved raising the leg in front of the body (Zhang, 2021), and exhibited a range of motion between 115 and 150 degrees. The knee joint displayed varied flexion ranges, ranging from 122 to 169 degrees, and additionally allowed for up to 57 degrees of internal rotation during climbing. The shoulder and elbow joints demonstrated a range of motion up to 180 and 132 degrees, respectively. Among the joints, the shoulder exhibited the maximum abduction of up to 88 degrees, whereas the knee joint showed minimal abduction (8.2 degrees).

Furthermore, certain body dimensions and angular parameters were evaluated manually. To facilitate this assessment, ten dynamic posture photos were selected and analysed using computer-aided design software, such as AutoCAD (Figure 7). This approach enabled a detailed examination of the body dimensions and angular measurements within the dynamic climbing context.

The data assessed using CAD software was subsequently collated with the manual body dimensions obtained during the observation session, following the guidelines provided by (ISO 8559:1989(en)). Overall, these measurements were found to be commensurable, meaning they were approximately the same or comparable.

The comparison of static and dynamic measurements showed that inner-leg length changed by approximately 2.5–13.5%, back length by 3–12.2%, and arm length by 4.5–26.5% across the selected postures. Together with the joint-angle results, these changes identify areas where garment patterns may require additional functional length or a different distribution of ease. The observed movement demands can therefore be considered in relation to their potential implications for garment pattern development. Table 2 summarises the main findings and corresponding patternmaking considerations, while recognising that these observations provide design directions rather than definitive pattern dimensions.

Figure 8 illustrates how the examination of dynamic anthropometry identified the most substantial dynamic elongation in climbing pants in the inner-leg region and

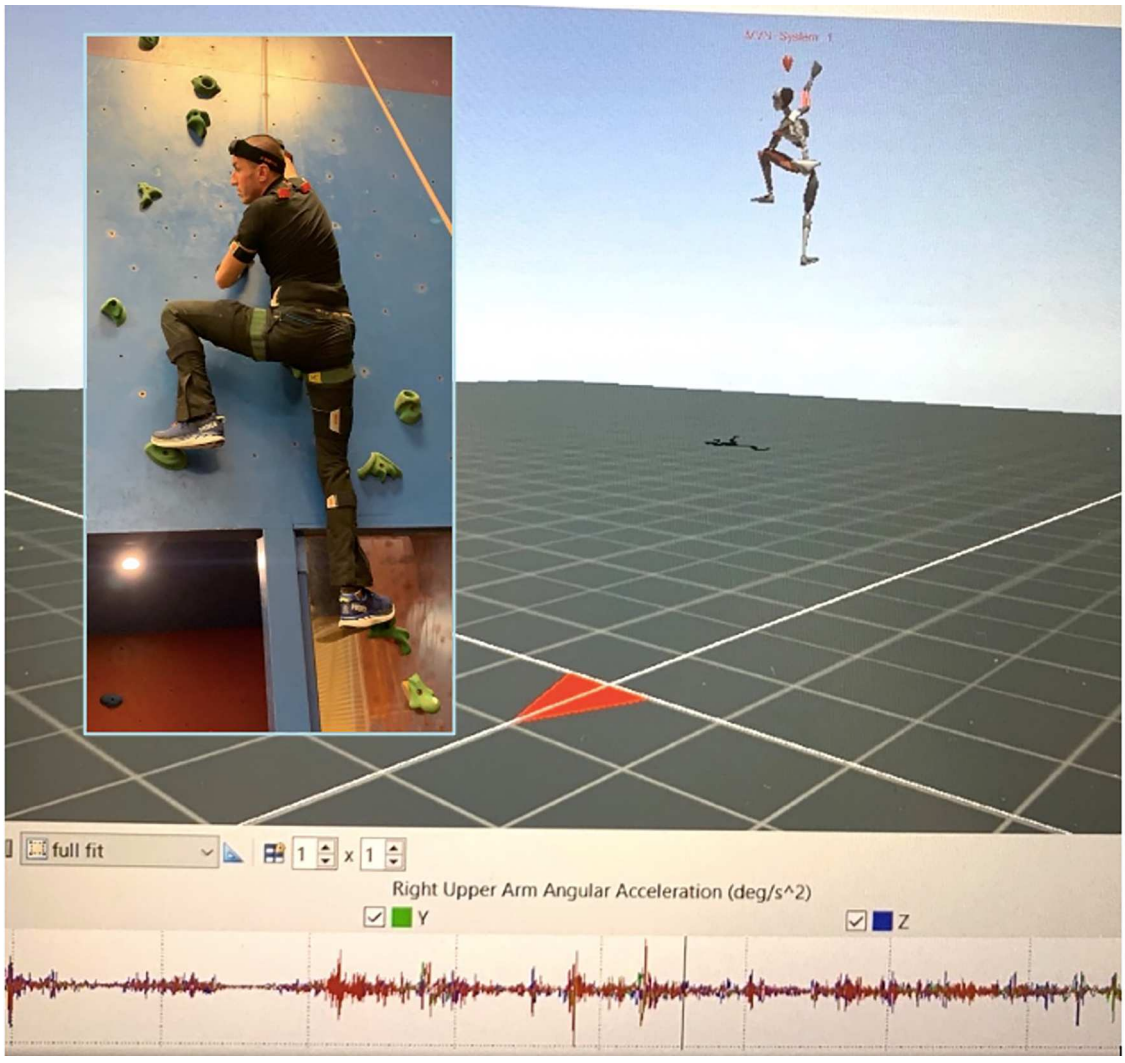


Figure 6. An example of the MVN and photo synchronisation.

in the distance from the waistline to the crotch fold. These findings indicate that the climbing-pants pattern requires additional length along the back crotch line and the inner seam of the back leg. Adjustments to the overall length of the pants may also be necessary to accommodate the dimensional changes associated with climbing movements.

Further advancements in clothing design, based on this study, encompass the enhancement of overall functional fit. For instance, to alleviate restriction of movements a gusseted crotch should be incorporated into the climbing pants to improve flexibility. In accordance with fabric pressure analysis (Novikova, 2025) and joint angle findings, it was determined that the elbows in jackets and the knees in pants endure the most constriction during climbing activities. Therefore, design enhancements in these specific areas should be deliberated upon. Few strategies may be employed to address these problematic areas:

- Utilisation of stretch textile materials characterised by both flexibility and high abrasion resistance.
- Implementation of pattern engineering techniques such as the incorporation of dynamic ease and/or the strategic addition and manipulation of extra darts.

5. Discussion

The dimensional changes of selected body regions were determined manually using CAD software in conjunction with photographic and video data and the manual body measurements obtained during the observation sessions. Xsens data were not used directly to establish these dimensional changes because the system primarily provides information on body-segment coordinates, velocity, acceleration, and related kinematic variables rather than direct measurements of dynamic body

Table 1. Parameters of joint angles while climbing.

Parameters (deg)	Abduction (max)	Adduction (min)	Internal Rotation (max)	External Rotation (min)	Flexion (max)	Extension (min)
Joint angles	First session					
Right Hip	49.23	−9.37	29.86	−16.99	119.75	-
Left Hip	43.84	−17.49	34.21	−10.58	119.7	−3.03
Right Knee	7.03	−24.68	31.77	−20.8	154.6	-
Left Knee	4.39	−26.52	31.75	−19.24	155.78	-
Right shoulder	69.94	−24.92	79.47	−41.5	106.15	−64.26
Left shoulder	62.87	−6.48	90.67	−53.9	111.01	−94.29
Right elbow	–	–	–	–	117.7	−11.92
Left elbow	–	–	–	–	131.77	−17.55
Second session						
Right Hip	44.41	−14.24	29.57	−22.89	132.28	−0.75
Left Hip	41.08	−19.78	32.11	−25.61	114.54	-
Right Knee	5.56	−29.79	27.21	−10.88	168.65	-
Left Knee	7.57	−21	12.57	−15.47	121.68	-
Right shoulder	33.09	−86.88	107.97	−83.75	180	−179.9
Left shoulder	78.37	−12.48	69.93	−73.09	119.17	−33.57
Right elbow	–	–	–	–	123.46	−7.05
Left elbow	–	–	–	–	100.24	−12.73
Third session						
Right Hip	48.95	−19.44	41.96	−15.55	144.1	−3.6
Left Hip	54.25	−31.8	47.49	−38.29	150.25	-
Right Knee	6.01	−45	57.11	−19.46	154.44	−0.44
Left Knee	8.21	−29.51	38.83	−20.82	163.1	−5.15
Right shoulder	-	−88.66	179.76	−179.96	179.82	−179.97
Left shoulder	87.78	-	89.41	−157.56	127.99	−136.71
Right elbow	–	–	–	–	128.2	−13.74
Left elbow	–	–	–	–	117.66	−17.29

dimensions required for garment pattern development. Furthermore, accurately determining changes between static and dynamic body landmarks presented methodological challenges. Unlike simulated movements performed on a level floor, the observation sessions involved actual climbing on a wall with multiple foothold and body positions at different vertical levels. Consequently, the relationship between body landmarks and the reference floor plane varied throughout the climbing sequence, which may have introduced some inaccuracy during post-processing and the comparison of static and dynamic measurements.

Subsequent analysis provided a more detailed interpretation of these observations when the data were re-examined in relation to dynamic

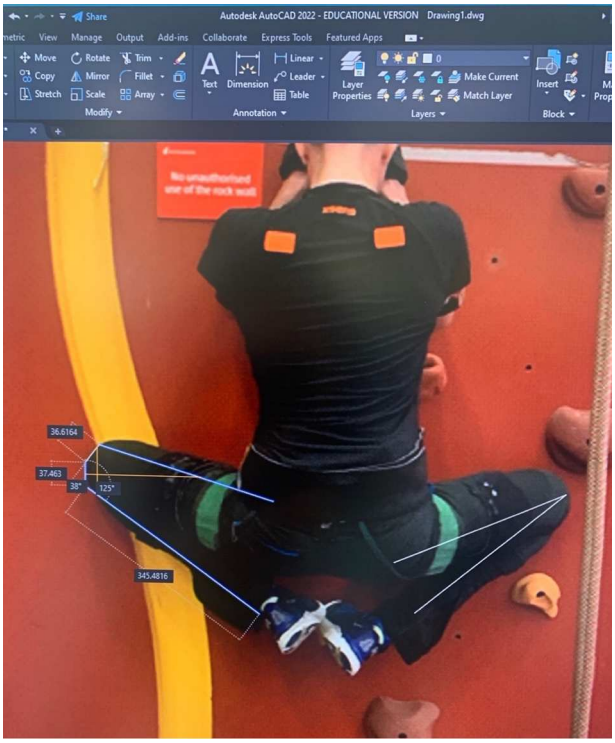


Figure 7. Assessment of dynamic posture using the CAD software.

Table 2. Translation of observed movement demands into patternmaking implications shows.

Observed finding	Patternmaking implication	Scope of interpretation
Inner-leg length: 2.5–13.5% change; high hip and knee flexion	Test additional functional length through the back crotch and inner leg, a crotch gusset or extended crotch construction, and articulated knee shaping.	The percentage change identifies a movement demand; it is not a direct instruction to add the same percentage to a finished pattern.
Back length: 3–12.2% change	Test redistributed upper-back ease through panel lines, a shaped yoke, pleats or stretch zones while maintaining harness compatibility.	The most suitable response depends on garment type, fabric recovery and seam placement.
Arm length: 4.5–26.5% change; shoulder and elbow flexion	Test sleeve and armhole mobility, articulated elbow shaping, and added functional length across the sleeve and upper back.	Material stretch can support these changes but should be assessed together with pattern geometry.

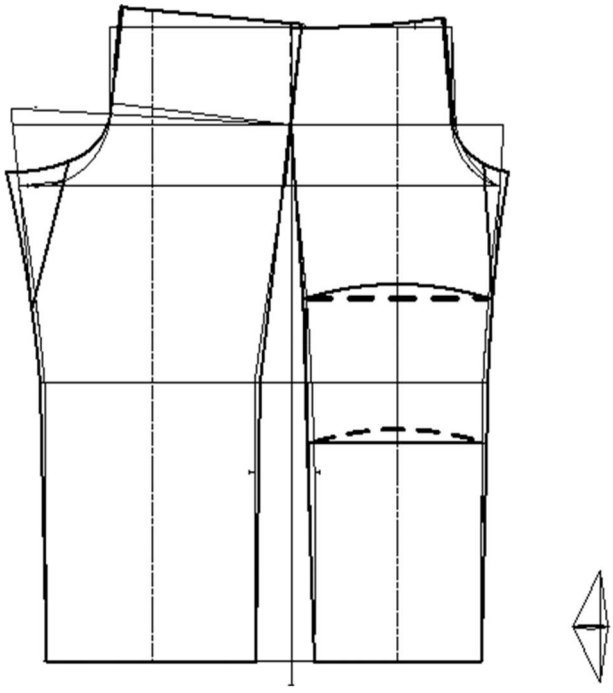


Figure 8. An example of modification of the patterns of climbing pants considering dynamics parameters.

anthropometry and garment pattern engineering (Novikova, 2025). This analysis identified approximate changes between static and selected dynamic climbing postures of 2.5–13.5% in inner-leg length, 3–12.2% in back length, and 4.5–26.5% in arm length (Novikova, 2025). These results demonstrate that changes in body dimensions during climbing are not distributed uniformly across the body. Instead, particular regions undergo greater dimensional changes and therefore require specific consideration during garment development. This provides a stronger connection between the observed biomechanical demands of climbing and potential garment construction strategies.

For the lower body, the combination of substantial hip and knee flexion and changes in inner-leg length suggests that movement allowance should be concentrated around the back crotch, inner leg, and knee rather than distributed evenly throughout the garment. Potential pattern-engineering responses include a gusset or extended crotch construction, additional functional length through the back crotch and inseam, and articulated knee shaping (see Figure 8). These construction features may be particularly effective when combined with appropriately selected stretch fabrics. However, fabric elasticity alone may not provide sufficient mobility where the underlying pattern restricts the body during highly flexed climbing positions.

Similar considerations apply to the upper body. Changes in back and arm dimensions indicate that the upper back, armhole, sleeve, and elbow regions require particular attention. Potential solutions include redistributing functional ease across the upper back, incorporating shaped or articulated panels, providing additional sleeve length, and introducing articulated elbow shaping. Such approaches may accommodate overhead reaching and combined shoulder and elbow movements while reducing excessive garment tension. The direction and placement of fabric stretch should also be considered in conjunction with pattern geometry, particularly in areas where the garment interacts with climbing equipment such as a harness.

The findings therefore provide evidence-based priorities for garment development rather than definitive pattern dimensions or universal ease allowances. The percentages reported by Novikova (2025) represent the approximate dimensional changes observed in the selected participants and postures and should not be interpreted as direct pattern-ease values applicable to all climbers. The appropriate pattern response will depend on several interacting factors, including garment type, fabric elasticity and recovery, construction methods, seam placement, and the interaction between the garment and climbing equipment. Consequently, the identified dimensional changes should be regarded as a basis for further pattern development and testing rather than as final construction specifications.

The scope of the present findings should, however, be considered when interpreting their design implications. The observational study involved only two experienced climbers and ten selected climbing postures, with dynamic dimensional measurements derived through CAD-supported image analysis. The findings consequently provide an indication of movement-related dimensional changes and identify priority areas for garment development, but they cannot be generalised to the wider climbing population or used to establish standardised movement-ease values. Differences in body morphology, climbing experience, technique, flexibility, and movement strategy may produce different dimensional changes between individuals.

Further research is therefore required to validate the proposed pattern responses through prototype development, fitting, and movement-based garment testing involving a larger and more diverse participant group. Testing across a broader range of climbing techniques, body sizes, and climbing postures would provide additional evidence for determining how dynamic dimensional changes should be translated into garment construction.

One possible direction for future research would be to develop a mathematical model describing the relationship between changes in body dimensions and

joint angles across static and dynamic climbing positions. Such a model could potentially be used to investigate movement-ease requirements across different body-size ranges and to examine how additional ease might be distributed across specific garment regions. If validated through further anthropometric data and prototype testing, the resulting relationships could contribute to the development of technical pattern specifications for rock-climbing clothing. This approach could provide a more systematic means of translating dynamic anthropometric and movement data into garment construction parameters and may support the development of evidence-based design guidelines for ergonomic climbing apparel.

6. Conclusion

The findings emphasise the importance of understanding the unique biomechanics and movement patterns associated with rock climbing. The angular parameters of the hip, knee, shoulder, and elbow joints have been identified, providing crucial information for developing clothing patterns that allow for an optimal range of motion and comfort during climbing activities. The incorporation of appropriate ease and dynamic ease allowances in the clothing design can ensure that climbers can move freely and comfortably while maintaining the necessary levels of flexibility and protection. Furthermore, the research acknowledges the limitations of using motion capture technology in capturing dynamic stretching characteristics and highlights the importance of combining manual measurements and CAD analysis to provide a comprehensive understanding of climbers' body dimensions and movement patterns.

The proposed design responses should therefore be treated as hypotheses for pattern development and wear testing rather than as universal ease allowances. Future research should evaluate prototypes across a range of climber body types, climbing techniques, and fabric properties, as well as examining their interaction with harnesses and other climbing equipment.

Author contributions

CRediT: **Aleksandra Novikova:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Writing – original draft, Writing – review & editing; **Donna Cleveland:** Supervision; **Frances Joseph:** Supervision.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Statement of ethics

Research stages that involve human research participants are covered by the Ethics Application 21/171, approved by the Auckland University of Technology Ethics Committee (AUTEC).

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