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Unveiling key user experience issues to facilitate user-centred design of inertial motion capture systems

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Abstract

Inertial motion capture has garnered considerable attention within the manufacturing industry for ergonomic assessments due to high reliability and fewer constraints compared to alternative posture tracking direct measurement tools. However, these wearable systems, while ensuring reliability and precision in the results, also introduce a degree of invasiveness. Hence, user experience becomes an important aspect for design and development of such systems. This paper reveals major user experience issues resulting from an experimental study for promoting user-centred design of wearable systems.

Keywords: user experience, user-centred design, industrial design, wearable systems, ergonomics

1. Introduction

With the advent of Industry 4.0, the growing emphasis on data-driven process planning has led to the widespread integration of wearable systems in the manufacturing sector, primarily for capturing human-centric data (Anes et al., 2023; Rosário and Diaz, 2023; Svertoka et al., 2020). The integration of wearable devices has seamlessly merged the physical and digital realms of manufacturing thereby creating an opportunity for real-time data processing and feedback for improvement of production processes (Kong et al., 2018; Rosário and Diaz, 2023). For fostering a safer workplace environment, these wearable systems can prove to be a cornerstone by facilitating a more accurate and reliable data collection as compared to the traditional approach of surveying for collection of safety related data (Prince et al., 2008; Wu et al., 2022; Zeng et al., 2022). This approach to workplace safety does not only reduce the chances of work-related musculoskeletal disorders (WMSD) and mitigate the workplace accidents but also infuses an awareness and sense of accountability in the organization (Stefana et al., 2021). The wearable systems also help in boosting productivity of the workforce by collection of data to pinpoint the causes of lag in production operations (Rosário and Diaz, 2023). Hence, the process of ergonomic assessments facilitating reliable data collection along with thorough analysis and subsequent exposure estimation becomes a linchpin for overall well-being and efficiency of the workforce.

Consequently, a range of tools has emerged for monitoring diverse ergonomic exposure data, such as force gauges for measuring required force application, surface electromyography (sEMG) for monitoring muscle activity, motion capture for tracking postures and so on (Feng et al., 2013; Lowe et al., 2019; Mudiyanselage et al., 2021). In the industrial context, generally, the decisions regarding the implementation of any ergonomic interventions rely on an exposure score calculated according to various criteria such as RULA, REBA, PERA among others which primarily rely on postural data. Hence, among the aforementioned range of tools, motion capture, has gained the most prominence given

the necessity of postural data collection and the potential for integrating these systems in the form of wearables (Salisu et al., 2023).
There exist many variations of the motion capture techniques. While marker-based optical motion capture is recognized for its accuracy of measurement, as it employs camera-based data collection, its practicality in industrial settings is limited due to susceptibility to occlusion-related issues (Ceseracciu et al., 2014). Inertial motion capture systems address these challenges with the usage of wearable sensors for data collection, utilizing multiple inertial measurement units (IMUs) affixed to various body segments to record orientation, position, velocity and acceleration (Salisu et al., 2023). This data is commonly used for identification of postures attained by the subjects with the help of relative angles of various body segments among other calculations. Subsequently, assessment criteria are applied to check whether the attained postures adhere to safe practices considering work-related disorders, or if adjustments are required. However, these systems involve a certain degree of invasiveness and therefore the quality of human interaction with wearable systems becomes an important consideration from the product design point of view which necessitates the study of usability, product acceptance and overall user experience of these wearable systems.
Over the past decade, there has been a growing emphasis on the aspect of human-centricity in the domain of research into design (Rautray et al., 2020). Therefore, there has been a focus on the study of various aspects such as usability, user experience design, human behaviour in design and the various methods of exploration for these aspects. Baskan and Goncu-Berk (2022) define user experience as a term that encompasses users' emotions, beliefs, preferences, perceptions, physical and psychological responses associated with the usage of a product before, during and after interacting with it. Lee and Chang (2010) states that the purpose of product design should not be only to fulfil specific functions but to deliver a satisfactory overall experience to the consumers. Jung and Chung (2014) state that the market acceptance of products depends hugely on the consumer's physical, and emotion connect and highlight the importance of user-centred design. Hence, considering the significance of user-centred design and the evolving realm of wearable devices in the manufacturing domain, this study explores the user experience issues in the context of inertial motion capture systems used for posture tracking in manufacturing tasks.

2. Literature review

Several papers have highlighted the importance of usability and user experience in design of wearable technologies and a number of studies have explored the user experience for wearable devices in various domains.
Andreoni (2023) points out the progressing domain of wearable devices making a mark on various aspects of our lives, such as fitness, health and safety tracking, and rehabilitation. The study highlights the availability of clear technical requirements for such wearable products but the lack of human centricity, wearability, and user experience related aspects in the design. In light of this, the paper puts forward a methodology consisting of a five-step approach for the study of usability: defining target users, conducting task analysis, preparing protocols and tools, executing usability experiments, and analysing and reporting data. The proposed methodology establishes a systematic framework for conducting usability studies for wearable devices thereby supporting research in the direction of usability, user experience and human-centricity of wearable devices.
Baskan and Goncu-Berk (2022) studied the user experiences associated with the usage of two distinct types of wearable devices including accessory based and textile based devices. The data for user experience study was acquired through surveys and the findings suggested the preference for textile based alternative as compared to the counterpart on the basis of user experience.
Zhang (2018) talks about the significance of user experience in context of human computer interaction (HCI) as well as non-functional products. The study conducted survey for the insights of youth on user experience related to wearable technology in general. The results include general opinions and expectations of youth about experience of wearable devices
Klaassen et al. (2017) studied the usability and effectiveness of a newly developed inertial motion capture system INTERACTION with regards to care professionals. This system measures the quality of movement (QoM) metrics in stroke patients and the study was aimed to assess how well the care

professionals utilise the system so that the gap between research and clinical implementation can be minimised.

Michaelis et al. (2016), talks about the acceptance or rejection rates of wearable devices more specifically fitness trackers, and the inter-relationship with user experience. The study utilised online product reviews to conduct quantitative and qualitative analysis and came up with key themes that seemed to affect user experiences with these devices such as usability, trust, motivation and wearability. Several studies such as Costa (2017), Braun and Clark (2019) and Byrne (2022) explain the motivation, framework and interpretations of qualitative thematic analysis for the study non-measurable aspects of user experience in design research. Costa (2017) conducted a usability study for qualitative data analysis software webQDA version 2.0 through content analysis. Braun and Clark (2019) propose a six step approach to thematic analysis discussed in detail in Section 3.4. Byrne (2022) highlights the different applications of various types of thematic analysis and explain the method of reflexive analysis in detail underscoring the importance of interpreter's own perception against inter-coder reliability the which makes the process stand out from the other forms of thematic analysis which rely on inter-coder reliability.

In conclusion, this literature review has clarified the current state of research in the domain of non-measurable aspects of user experience for wearable devices, and the approaches instrumental for conducting such studies. The scarcity of research on the user-centricity of inertial motion capture systems was observed and thereby, taking into account the methods of qualitative analysis, mentioned in design research, this study was conducted for the exploration of various attributes of user experience with the usage of inertial motion capture in manufacturing domain.

3. Methodology

There were four sections in the approach followed for this paper beginning with a market study, followed by experimental study, quantitative analysis and qualitative analysis. Figure 1 depicts a summary of the methodology

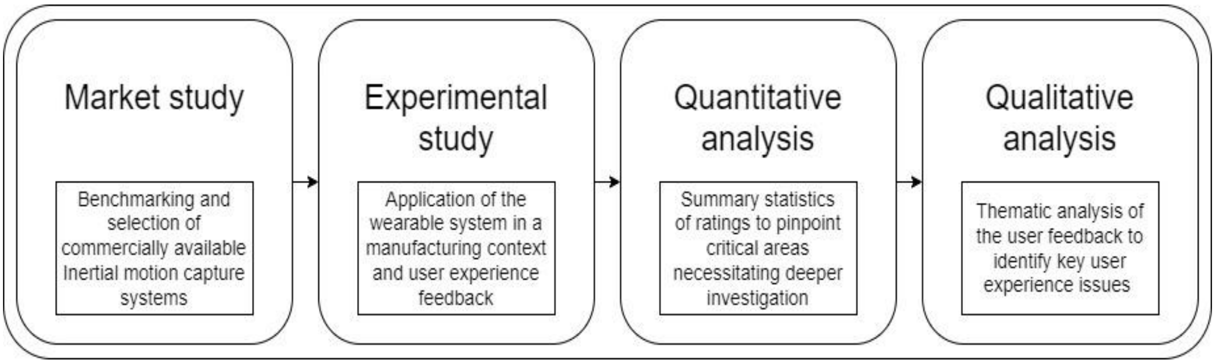


Figure 1. Summary of the study methodology

The rationale and methods employed for each of these sections is explained in the following subsections.

3.1. Market study

Through a concise and targeted market study, it was observed that a broad array of inertial motion capture systems is commercially available. These systems of different makes were studied for their features, limitations, and suitability to be implemented in an industrial setting. After a thorough market study, Xsens Awinda suit was selected for the user experience assessment as it is deemed to provide highly accurate and reliable postural data while incorporating advanced data processing algorithms for minimising the effect of gyroscope drift and noise accumulation in the raw data captured by the Inertial Measurement Units (IMUs), thereby displaying a lot of potential for industrial implementation.

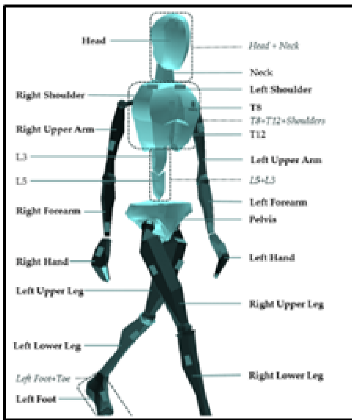
Xsens Awinda motion capture suit consists of seventeen distinct IMU sensors with attachment belts, gloves, jacket for various sensor placements on the body parts for accurate postural estimation and Awinda station for wireless data transmission from the attached sensors.

3.2. Experimental study

After selection of the inertial motion capture system, 36 participants including 20 males and 16 females within the age range of 23 – 30 years performed a laboratory simulated manufacturing task wearing the Xsens Awinda suit. The manufacturing task comprised of assembly and disassembly of a Boeing aircraft wingbox as shown in Figure 2. The participants were provided with the instructions for sequence, contents and tools for some simple standard operations involved in the assembly and disassembly. The experimental protocol was approved by the institutional ethics committee.

Figure 2. Task performance with sensor setup

Subsequent to task completion, the participants were provided with feedback form for collecting details of their user experience with the motion capture suit while performing the manufacturing tasks. The feedback form included 5 attributes of user experience and for each of these attributes, the participants rated the difficulty or concerns on a 5-point Likert scale corresponding to each of the 17 sensors included in the Xsens Awinda suit (Figure 3). Additionally, the feedback form also included spaces for mentioning the details of the activities associated and reasons for the user experience concerns along with open-ended response sections for any additional details or remarks that the participants would want to include regarding the overall feel, usability, and experience of working with the motion capture suit in general.



Sensor	Discomfort					Burden					Emotions				
Head	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
R shoulder	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
L shoulder	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Sternum (T8)	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
R upper arm	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
L upper arm	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
R forearm	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
L forearm	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
R hand	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
L hand	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Pelvis	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
R upper leg	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
L upper leg	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
R lower leg	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
L lower leg	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
R foot	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
L foot	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5

Sensor	Distraction					Reason	Flexibility issue					Associated activity
Head	1	2	3	4	5		1	2	3	4	5	
R shoulder	1	2	3	4	5		1	2	3	4	5	
L shoulder	1	2	3	4	5		1	2	3	4	5	
Sternum (T8)	1	2	3	4	5		1	2	3	4	5	
R upper arm	1	2	3	4	5		1	2	3	4	5	
L upper arm	1	2	3	4	5		1	2	3	4	5	
R forearm	1	2	3	4	5		1	2	3	4	5	
L forearm	1	2	3	4	5		1	2	3	4	5	
R hand	1	2	3	4	5		1	2	3	4	5	
L hand	1	2	3	4	5		1	2	3	4	5	
Pelvis	1	2	3	4	5		1	2	3	4	5	
R upper leg	1	2	3	4	5		1	2	3	4	5	
L upper leg	1	2	3	4	5		1	2	3	4	5	
R lower leg	1	2	3	4	5		1	2	3	4	5	
L lower leg	1	2	3	4	5		1	2	3	4	5	
R foot	1	2	3	4	5		1	2	3	4	5	
L foot	1	2	3	4	5		1	2	3	4	5	

Figure 3. User experience feedback form

3.2.1. User experience attributes

The five attributes to consider for measuring the overall user experience of the inertial motion capture suit, namely, 1) Discomfort, 2) Burden, 3) Distraction, 4) Flexibility issue, and 5) Emotion were shortlisted after a comprehensive literature search on the user experience aspects for wearable devices in various domains such as sports, ergonomics, rehabilitation and animation industry (Baskan and Goncu-Berk, 2022; Knight and Baber, 2005; Pearson, 2009). Participants were provided with the following explanations of these attributes and corresponding Likert scale descriptors.

1. Discomfort: pain, uneasiness, irritation, pressure etc. on physical level resulting from wearing this particular sensor of the motion capture suit.
   Likert scale descriptors: 0 – no discomfort, 5 – high level of discomfort
2. Burden: cognitive load, stress, worry due to wearing this particular sensor of the motion capture suit.
   Likert scale descriptors: 0 – no burden, 5 – high level of burden
3. Distraction: not being able to focus on the operations to be performed because of wearing this particular sensor of the motion capture suit.
   Likert scale descriptors: 0 – no distraction, 5 – high level of distraction
4. Flexibility issue: reduced mobility of body parts, obstructed movement due to this particular sensor of the motion capture suit.
   Likert scale descriptors: 0 – no Flexibility issue, 5 – high level of Flexibility issue
5. Emotion: overall concerns while wearing this particular sensor of the motion capture suit such as concerns about appearance, relaxation etc.
   Likert scale descriptors: 0 – no concerns, 5 – high level of concerns

3.3. Quantitative analysis

The quantitative analysis involved investigation of the summary statistics of the Likert scale ratings to get a clear picture of occurrence of the user experience concerns with corresponding sensor placements. As a result of the ordinal nature of the rating data, median of ratings by all the participants for each of the 17 sensor placements under the 5 attributes was calculated as the measure of central tendency of the rating data as shown in Figure 4.

These summary statistics were used to identify the particular sensor placements that were implicated in giving rise to suboptimal or unsatisfactory user experiences. The reasons mentioned corresponding to these sensor placements were studied along with other additional comments from the open-ended response sections to get detailed insights into the causes for these user experience issues. Finally, these reasons and additional comments were utilised for a qualitative thematic analysis to identify themes of user experience challenges to unveil user-centred design opportunities.

3.4. Qualitative analysis

In order to pinpoint the user experience issues, a reflexive thematic analysis was conducted from the feedback of the participants. Braun and Clarke (2019) proposed a six-phase thematic analysis approach. Accordingly, the following steps were undertaken to discover the key themes specifying user experience challenges.

1. Data familiarisation: The reasons for suboptimal user experience ratings were studied thoroughly. Additional comments from the open-ended response section were read and mapped with the corresponding sensor placements to put the data in context and better comprehend it.
2. Generation of initial codes: The text fragments, phrases, and sentences conveying significant information regarding the interaction of participants with the motion capture suit were highlighted and labeled to generate initial codes.
3. Theme generation: The labeled excerpts from the feedback were collated in order to identify any existing patterns to form initial themes. These patterns were detected based on the similarity of the user experience issues mentioned in terms of their mode of occurrences, affected body parts, frequency of occurrence and so on.

4. Theme review: The initial themes of user experience issues were studied carefully to ensure that each theme incorporates unique and coherent issues. Themes conveying similar challenges as identified by the included subthemes, were merged into one. Similarly, very diverse challenges categorised within a single overarching theme were split into multiple user experience issue themes.
5. Theme definition and naming: The resulting themes were defined by abstraction of the key challenges listed under the overarching themes to generate a theme name which effectively incorporates the essence of each of the underlying challenges.
6. Report generation: Finally, the identified themes of key user experience issues and underlying challenges were utilized to develop a thematic map. This thematic map was used to clearly display the interconnections between the underlying challenges and the identified primary themes as shown in Figure 5.

4. Results

Figure 4 includes the plots of medians of Likert scale ratings for each of the sensor placements and user experience attributes.

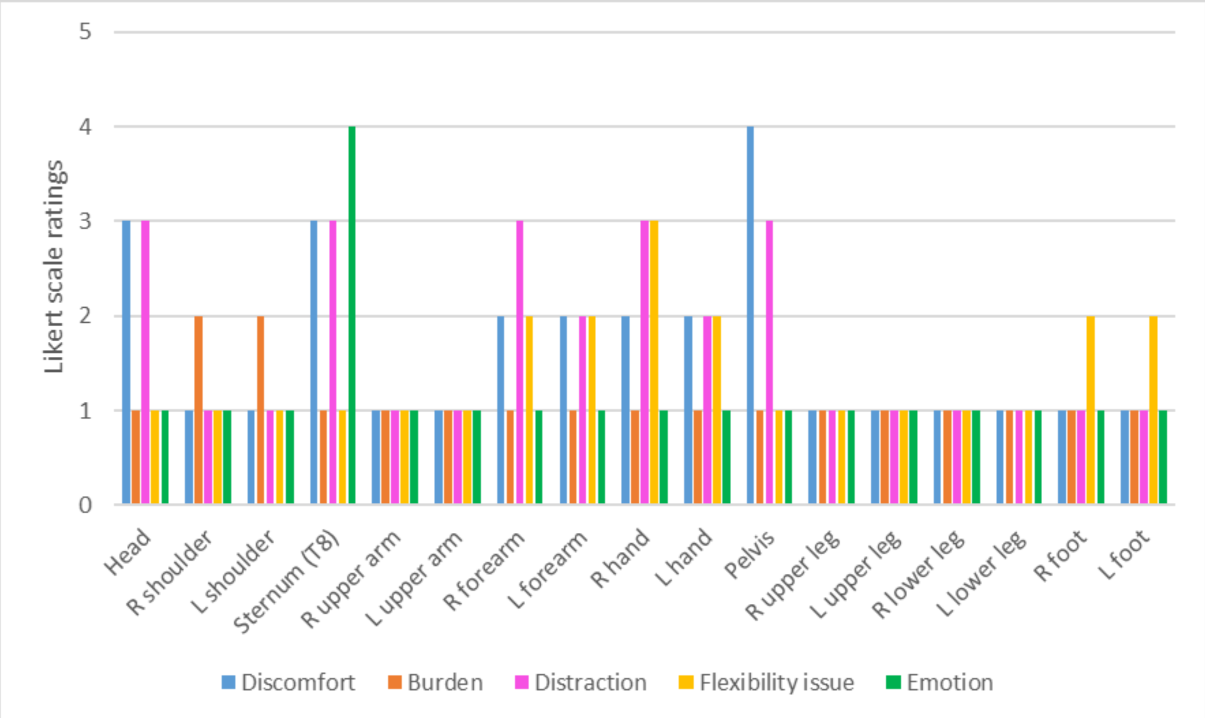


Figure 4. Medians of Likert scale ratings for each user experience attribute

It is evident from Figure 4, that a distinct set of few sensor placements are critical from the user experience point of view for each of the five attributes. For instance, for the attribute of discomfort, the critical sensor placements include head, hands, forearms, sternum, and pelvis while for the attribute of burden only the sensor placement of shoulder is critical. Similarly, the critical sensor placements for each of the attributes were identified in order to streamline the data involving subjective answers. Participants' descriptions for these sensor placements regarding reasons for high ratings along with miscellaneous data on overall user experience were considered for further qualitative thematic analysis. The resulting thematic map from the qualitative analysis is shown in the Figure 5.

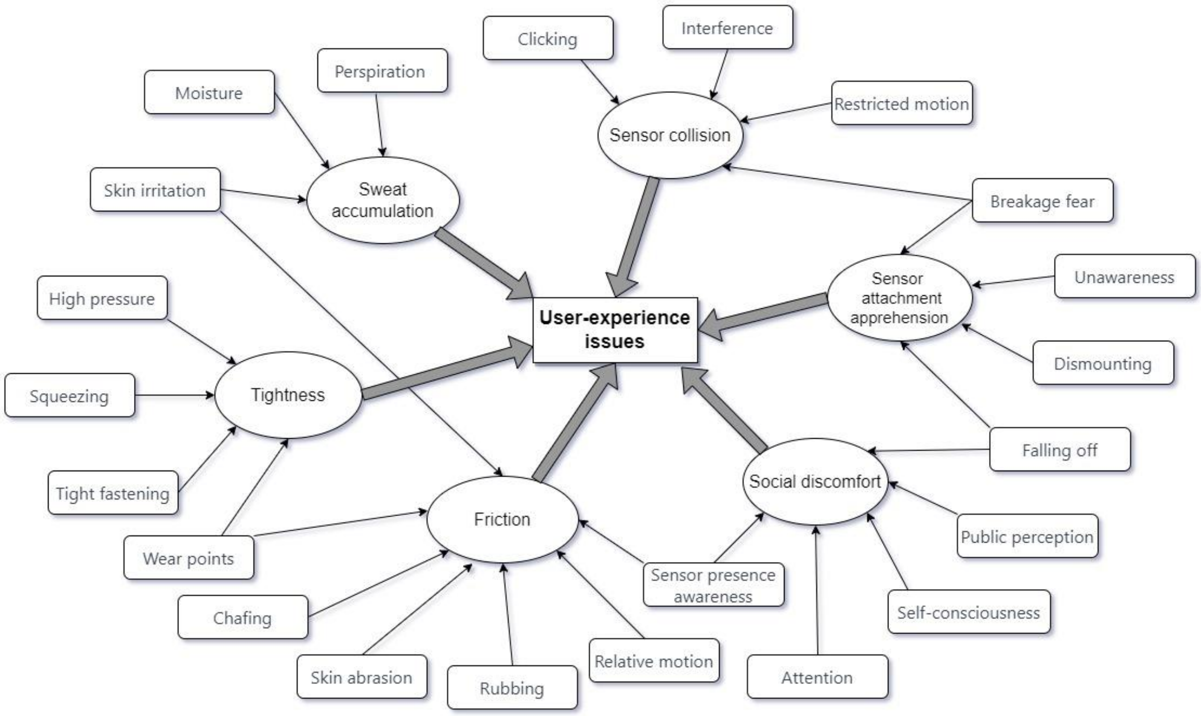


Figure 5. Thematic map with key user experience issues and underlying challenges

Figure 5 clearly depicts six themes of key user experience issues along with underlying challenges identified from the response of the participants regarding their interaction with the motion capture suit in context of manufacturing tasks.

Outlined below is a brief description of each of the identified themes.

- Sensor collision: this theme includes the issue of collision of IMU sensors attached to the participants with other sensors or objects which the task involved. As a result of this issue, the tasks were impeded with the implementation of the motion capture suit. This theme was identified with the keywords from the excerpts of "flexibility issue" attribute such as clicking, interference, restricted motion, clashing, impact and so on.
- Sweat accumulation: this theme includes the issue of uneasiness due to the presence of moisture on the skin as the belts used for sensor attachment resulted in accumulation of sweat as the participants were engaged in the manufacturing task. As a result of this issue, the participants felt discomfort and distraction and were not able to fully concentrate on the task as mentioned in the excerpts from the aforementioned attributes of "discomfort" and "distraction".
- Sensor attachment apprehension: this theme includes the concerns of participants regarding the security or safety of the sensors. This was evident in cases of the sensor placements which were not visible to the users such as the sensors placed at the shoulders. The keywords that established this theme include breakage fear, dismounting, falling off, etc. in context of the attributes of "burden" and "distraction".
- Tightness: this theme includes the issue of tightness of attachments used to secure the sensors on the body parts. Although tight attachments are necessary to ensure the reliability of the captured postured data and are one of the fundamental design requirements for wearable sensors in this context. Nevertheless, as a result, the participants reported concerns such as redness, wear points, squeezing among others in the response in conjunction to the attributes of "discomfort" and "distraction".
- Social discomfort: this theme overarches the concerns of the participants regarding their public image as they were engaged in the task with the sensors attached. Several participants had positive perception of their public image while others had a negative perception as apparent from the excerpts under the attribute of "emotion".

- Friction: this theme incorporates the instances of relative motion between the sensor attachments and the skin of the wearer. As a results of this issue, problems such as skin abrasion, wear points, chafing among others were mentioned under the attribute of “flexibility issue”.

These themes provide a detailed insight into the feel, functioning and overall experience of the various components of the motion capture suit from the standpoint of interaction with humans. These insights are instrumental for a user-centred design.

5. Discussion

Following the quantitative and qualitative analysis of the feedback on the five attributes of user experience, the study has successfully demarcated the mentioned challenges, participant’s preferences and opinions from the responses into six distinct and coherent themes of user experience issues regarding the inertial motion capture Xsens Awinda suit. These identified themes open the door to a multitude of user-centred design opportunities on diverse aspects of design and development of inertial motion capture systems as well as other similar wearable devices in general. A closer look at the themes and the underlying challenges provides clarity in terms of the critical design parameters from the standpoint of a user-centred design for inertial motion capture suits such as the form factor of the sensors, material, fit of the attachments and so on.

Additionally, the study provides focused design insights for specific sensor placements as both quantitative and qualitative data were collected for each sensor placement. Specific design considerations for each attachment piece can be drawn for improvements in the five user experience attributes investigated in the study. For example, in the attribute of emotion, the sternum sensor placement is critical as per the Likert scale ratings, subsequent study of the subjective feedback regarding these sensor placements reveals the concerns of participants about appearance with the application of these sensors attachment pieces and leads to the user experience issue theme of “social discomfort” in reflexive thematic analysis. This suggests that aesthetics is an important design consideration for the design of sternum sensor attachment pieces.

Another interesting observation from the research findings includes the frequency of occurrence of different user experience issues. Figure 6 depicts the number of incidents mentioning occurrence of a particular theme for each of the identified themes.

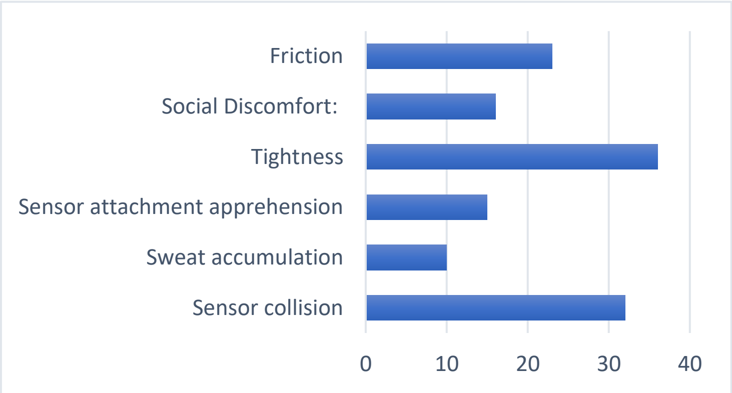


Figure 6. Incidents of occurrence of identified themes

The instances of mention of any user experience issue by the participants may vary due to several factors such as their perception of discomfort, discerning eye for recognising various issues, tolerance level, and other subjective considerations. However, this observation can still be instrumental for design requirements prioritization as one way to gauge the severity of a specific issue based on how broadly it is reported.

Consequently, the study findings can be used to formulate a focused set of design requirements to address each identified issue in order to improve the user experience of such wearable systems. Furthermore, the participant’s responses in terms of number of mentions of specific issues, the perceived severity of issues apparent from the excerpts may form the basis of requirement prioritisation for the design and development process.

6. Summary, future work and conclusion

The primary objective of this study was to identify major challenges that lead to a suboptimal user experience with the usage of inertial motion capture systems, given the significance and potential of such systems for promoting safety and productivity in the manufacturing domain. Beginning with a market study to select a suitable product from the standpoint of industrial implementation, Xsens Awinda suit was utilized for conducting an experimental study involving manufacturing tasks with feedback form for getting responses on five attributes of user experience. Following the quantitative and qualitative analysis of the feedback, six distinct themes of user experience issues were successfully identified which include Sensor collision, Sweat accumulation, Sensor attachment apprehension, Tightness, Social discomfort and Friction.

The research findings are instrumental for various stages product design. These stages include formulation of list of design requirements to improve user experience of such wearable systems corresponding to each identified theme and underlying challenges and requirement prioritisation to obtain a focused list of requirements that are critical for user-centred design to improve the human interaction, usability, and overall experience of usage of inertial motion capture systems.

While the study successfully identified a range of user experiences issues critical to user-centred design of the inertial motion capture systems, certain limitations to the study must be addressed. The study involved a specific lab simulated manufacturing task and the user experience challenges were identified in the context of the said task. Playing with a wider range of manufacturing operations involving workers from manufacturing shop floors may lead to a wider spectrum of user-centred design opportunities. Hence, future research work includes working with diverse manufacturing scenarios for identification of user experience issues with the usage of inertial motion capture systems. Since, this study was dedicated towards the identification of user experience issues in the context of inertial motion capture systems, further research directions involve user-centred design and development of such systems incorporating these insights to improve the user experience and facilitate industrial implementation.

In conclusion, this study serves as a stepping stone for further research and development in the field of user-centred design of wearable devices. Assimilation of the design insights highlighted in this study in terms of user experience issues into future design iterations has the potential to significantly enhance user satisfaction and overall performance, fostering greater acceptability and advancements in inertial motion capture technology. Design and development taking into consideration the identified themes, hold the capacity to culminate into products that coalesce seamlessly with the evolving needs and norms in the manufacturing industry as well as with the preferences of the users promoting extensive industrial implementation.

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