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A pain in the neck: prototyping and testing of a patient simulator neck for spinal immobilization training

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ABSTRACT

This paper presents the development and user-testing of a novel concept for patient simulators, aiming to enhance spinal immobilization training. Iterative prototype interactions with critical stakeholders revealed a need for evidence-based guidelines and training for suspected neck injuries. A realistic and compliant neck prototype with sensor feedback was developed to address the need for objective performance metrics. The conceptual prototype was used in an experimental study ($n = 12$) to obtain subjective and objective feedback on its characteristics and use in medical training. In the experiment, users were asked to perform spinal immobilization techniques on a simulator while sensor data recorded head and neck movements. Furthermore, a Likert-scale questionnaire and subjective feedback were gathered. Results are used to discuss proposed performance metrics and whether they can be used as quality performance indicators for formative and summative training feedback. The results also suggest the neck prototype to realistically simulate an unconscious patient regarding the obtained range of motion and spinal compliance.

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Patient simulator; medical training; spinal immobilization; sensor; prototyping; healthcare design

Introduction

In medical cases where a patient has been subjected to traumatic accidents and needs care and transport from an out-of-hospital location, the neck of the patient is particularly important. Since the neck is less protected than the rest of the spine, avoiding eventual further damage to the spinal cord is crucial, as this could lead to paralysis or death. Cervical spine injuries represent 29% of all injuries to the spinal cord (Domeier et al. 1997). Of these, Theodore et al. (2013) estimate that up to 25% of spinal injuries occur after

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the initial impact, during medical treatment of the patient, or transportation to the hospital. High-quality medical treatment at the trauma site is essential as the mortality rate drops between 48.3 and 79% to 4.4 and 16.7% after the patient is admitted to the hospital (Sekhon et al. 2001). Hence, medical personnel need to be well-versed in handling a suspected spinal injury, and there is a need for adequate equipment to facilitate such training.

Guidelines and training of suspected neck injury treatment and care

If a spinal injury is suspected, the standard procedure has been to apply full immobilization of the patient (White, Domeier, and Millin 2014; ACS-COT 2018). However, several studies have shown the use of supporting equipment such as cervical collars and a backboard can cause problems like increased pain (Papadopoulos et al. 1999), increased intracranial pressure (Lemyze et al. 2011; Davies, Deakin, and Wilson 1996), and ultimately increased mortality rate in trauma cases involving penetrating spinal injuries (Vanderlan, Tew, and McSwain 2009; Haut et al. 2010). Thus, spinal motion restriction, referred to as SMR, has risen as an alternative to traditional spinal immobilization (Swartz et al. 2018). Using SMR, the patient is immobilized either manually or by applying a cervical collar. In this case, a medical professional is responsible for keeping the neck as still as possible during the assessment, treatment, and transportation.

When treating and transporting trauma patients with suspected spinal injuries, it is not evident what movements are considered optimal (or acceptable). Furthermore, which approach (full immobilization or SMR) that accounts for the best results in different scenarios is ambiguous, considering unique patient characteristics, different injuries, and the challenge of obtaining measurable and comparable data in out-of-hospital events.

In training and simulation of trauma scenarios, using standardized patients, and real human markers is often valuable. However, for real people to simulate an unconscious patient, not restricting neck movements, is challenging. Furthermore, performance evaluation and feedback are subjective, as it is based on external observations or experience from the human actor. Therefore, human patient simulators are widely used in training of trauma scenarios, as an alternative to human actors.

Human patient simulators

The use of human patient simulators (or mannequins) in medical training, is an expanding field aiming to replicate clinical scenarios in a safe and repeatable environment (Nehring, Ellis, and Lashley 2001). Several studies have suggested that the transfer of knowledge using human patient simulators, is superior to traditional teaching methods such as interactive case studies (Cant and Cooper 2010; Howard et al. 2010).

For patient simulators to be effective in training, the design needs to enable dextrous hands-on procedures and patient handling that can facilitate transfer of learning back into clinical scenarios (Issenberg et al. 2005). Current patient simulators, however, are considered rigid, and have limited humanlike mobility, range of motion, and tactility. Furthermore, training of pre-hospital treatment is also a field that lacks key performance feedback to trainees, especially regarding suspected neck injuries and neck immobilization.

Objective feedback in medical simulation training

Objective feedback in simulation-based medical training affects the learning outcome and retention of skills for various procedures and medical interventions (McGaghie et al. 2010). One example is the low-dose high-frequency skills training of cardiopulmonary resuscitation (CPR) using mannequins equipped with sensors providing objective feedback and quality improvement metrics (Spooner et al. 2007; Sutton et al. 2011). Feedback should be given during the learning experience, and is an important for retention of skills, and knowledge (Issenberg et al. 2005). Feedback given to trainees could be both formative and summative, but should be supported by objective performance indicators (McGaghie et al. 2010).

Aim and scope

This paper aims to showcase the development and testing of a new neck concept facilitating realistic interactions, as means of training for real patient encounters. The new neck, its functionality, and obtained sensor data will be presented and used to drive a discussion on the applicability of it to be used in medical training. Data obtained from testing will be reviewed and discussed considering trainee performance feedback and quality metrics for patient handling and neck immobilization. The development of a new neck was initiated to explore opportunities for future simulator neck topologies and functionality. As the project is considered a pre-requirement engineering design task, the scope has been to elicit requirements and understand user-needs. Furthermore, the project aim has been to prototype a solution and explore the potential for this to improve (and inform) medical training for suspected spinal injuries.

Prototyping a new neck by Iterative designing, building, and testing cycles

Development process

In the project of creating a new neck, the team utilized a highly iterative and prototype-driven development approach. This was to rapidly generate prototypes that could be tested with users, to gain access to experience-based tacit knowledge and making the user-needs tangible (Auflem, Falch Erichsen, and Steinert 2019). Prototypes were continuously designed, built, and tested to bring answers to open design questions (Ege et al. 2021). When interacting with users and stakeholders, prototypes served as a common ground for both gaining tangible feedback and inform further development (Houde and Hill 1997; Santos et al. 2021).

The following stakeholders were used for consultation through interviews, prototype interactions, and concept testing:

- Paramedics
- 5th year medical students working part time as ambulance personnel
- PhD candidate in neurosurgery

Iterative development of prototypes and testing

The development of the new neck concept can be described as iterative consultation-design-build-test cycles. A timeline, shown in Figure 1, visualizes this process in retrospect, highlighting the milestones being key prototyping activities and iterations.

Initially, the team conducted interviews with potential users regarding the routines and procedures during trauma scenarios and the shortcomings in simulation-based training. This need-finding uncovered the lack of flexibility in current mannequins to be a big limitation. It was stated that current simulators are generally not suited to the required interactions during trauma scenarios, due to limited range of motion and compliance. This was showcased by movements and handling of a widely used trauma simulator. It was noted that care and handling of suspected neck injuries are an important part of training, and that a flexible neck would enable spinal immobilization to be simulated more realistically.

Based on the insights uncovered through need-finding, the first prototype, *iteration 1,* was created using a biomimetic approach. By stacking rigid discs and silicone bushings in an alternating pattern, the movement could more closely imitate that of the human neck anatomy. Suspending the discs by spring-loaded wires, the stiffness of the neck could also be altered from selection and pre-tensioning of the springs. This allowed for a similar range of motion to a human neck. This was uncovered by empirical testing, using an existing mannequin head to observe and compare prototype performance with real human head movement and anatomical constraints.

In *Iteration 2,* replacing the flat discs with 3D printed elements, the bending radius, and degrees of freedom could be restricted by the topology of each disc element. During user-testing of this prototype, it was noted the

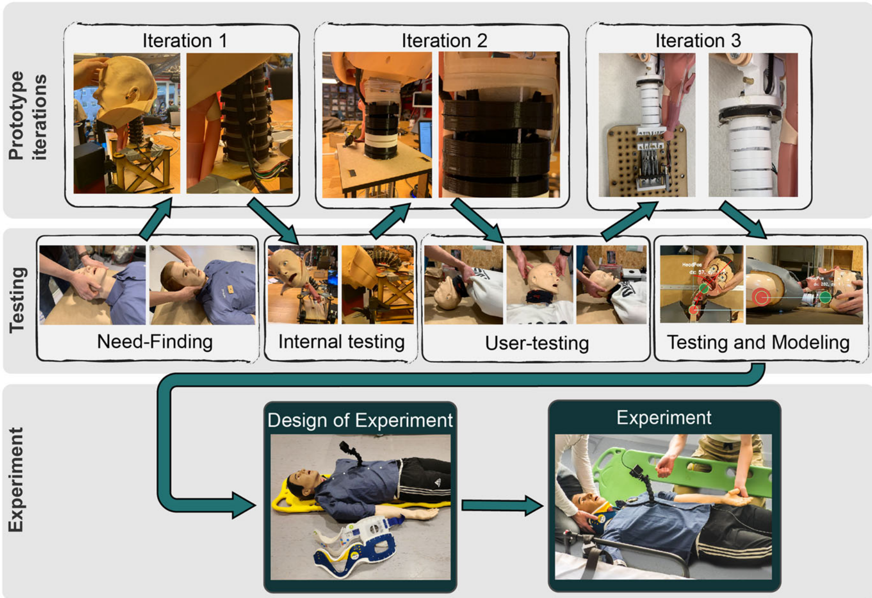

Figure 1. Prototyping activities in the project showing the iterations, the tests performed, design of experiment, and performing the final user-test. The setup, design and execution of experiment (dark boxes) will be further described in following sections.

looseness of the neck could resemble an unconscious patient, and that the lateral flexion felt realistic. However, the flexion and extension were missing, as the joint between the top vertebra and skull was not considered in the prototype. It was also noted the rotation of the head is mainly observed in this joint. Furthermore, an important finding during this user-testing was the lack of objective measurements and training performance indicators when it comes to suspected neck injuries. While it is evident that mitigating movements and strain to the neck is important, what type and magnitude of movement that could harm or cause further injury is not well understood nor researched.

Iteration 3 was designed to substitute the existing neck assembly in (but not restricted to) the SimMan3G from Laerdal Medical, a commonly used medical simulator (Shinnick and Woo 2013). Figure 2 shows the conceptual prototype and the different components making up the neck assembly. Four wires are led through the discs, evenly spaced in the four main directions of motion. Each wire is coupled in series with a spring, and all springs are pre-tensioned to the same level. By moving the head, the springs will either have a positive or negative relative displacement.

To address the lack of objective measurements and performance indicators, each spring was connected to a sliding potentiometer. The joint between the neck and head was equipped with rotary potentiometers at the

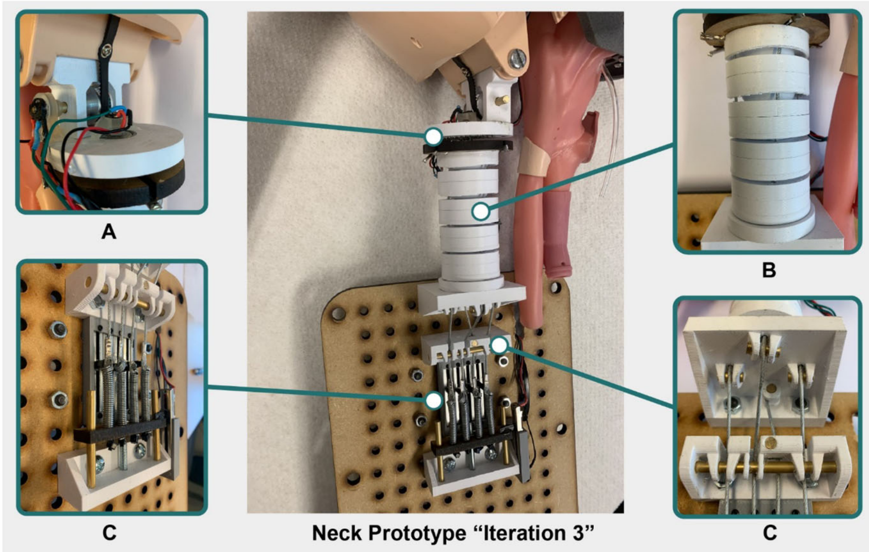

Figure 2. The design of the conceptual prototype (iteration 3). (A) Rotation and tilt recorded by rotary potentiometers. (B) 3D printed discs emulating the vertebrae. (C) Wires coupled in series with springs, with sliding potentiometers measuring the spring displacement. (D) Pulley system for wire routing.

rotational and tilting axis. This way, the spine's relative movement and the head's relative rotation and tilt can be recorded.

Modelling neck behaviour

Continuum robotics principles allows for modelling of suspended element structures, such as the neck in the developed prototype. This has been shown in a variety of applications such as artificial muscles (Pritts and Rahn 2004), surgery equipment (Chen, Pham, and Redarce 2009; Kato et al. 2015), and artificial human fingers (Suzumori, Iikura, and Tanaka 1992). Despite robots having different coordinate frames and analytical formalisms, Webster and Jones (2010) describe theoretical modelling that apply to all continuum robotics that can be assumed to express piecewise constant curvature (Rao et al. 2020).

However, the design of the neck prototype is not ideal and hence, relying solely on the ideal model is not feasible. Thus, empirical measurements using video tracking was performed, and the results were compared to the ideal model. The main objective was to correlate the spring displacements to the spine's angle, to track the neck and head's motion during handling.

Using OpenCV, as seen in Figure 3(A), a computer vision library and toolkit, a local coordinate system (green marker) was created relative to the red marker on the torso, with the x-axis (y-axis for lateral tilt) aligned with the green marker. The relative displacement of the green marker was then

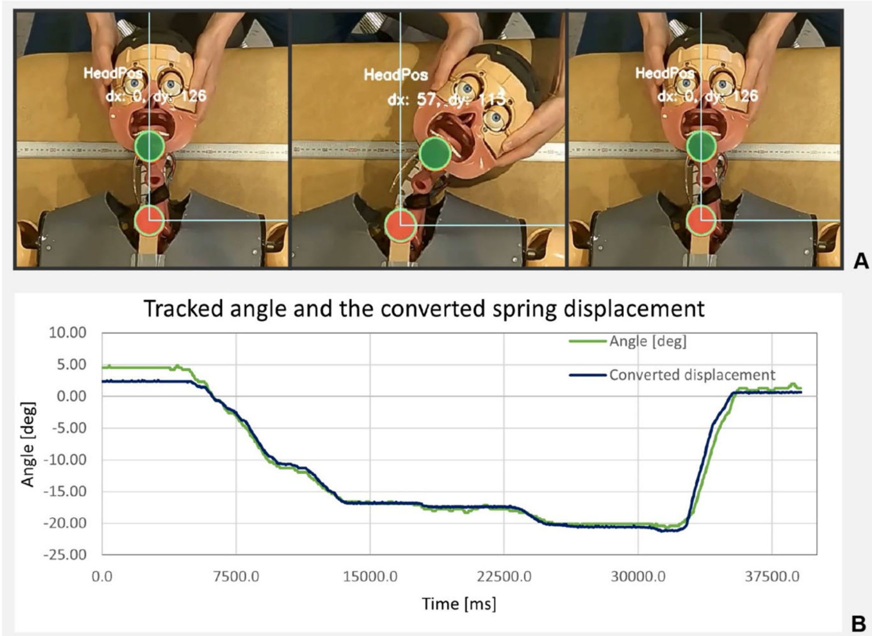

Figure 3. Tracking frames for the lateral flexion (A) and the corresponding graph (B) showing both the tracked angle and the converted displacement from the sensor readings. The same approach was repeated for the other directions (and spring displacements).

measured accurately based on the number of pixels it moved while moving the head to its extremes. Synchronizing the sensor readings with the derived angles from the video tracking can be seen in Figure 3. By dividing the tracked angles by the measured spring displacements, correlation factors could be derived for the different degrees of freedom. The angles from the spring displacements represent the frontal and sagittal components of the angular motion of the neck.

A linear correlation factor was also found for the relation between the spring displacement and the top of the spine's deviation from the neutral axis. The correlation factor for each spring, for both angular and distance conversion, is shown in Table 1.

Design of experiment

To maximize learning potential from the developed prototype, a structured experiment was designed. Based on mixed-method research, both objective and subjective data was captured and analyzed. The aim of the experiment was to, firstly, gain subjective evaluations of the performance and characteristics of the prototype, and secondly, to gather and analyze objective data on simulated patient handling and spinal immobilization techniques.

Table 1. Correlation factors for the angular and translational displacement for the four directions of movement.

Motion and affected spring	Correlation factor [degree/mm]	Correlation factor [mm/mm]
Backwards tilt (Front spring)	1.4402	4.53070
Forward tilt (Back spring)	1.0793	5.40365
Lateral deflection (Right spring)	1.7438	3.40950
Lateral deflection (Left spring)	1.7438	3.40950

Participants

Twelve users with relevant background and experience participated in the experiment. Each participant's gender, general age, occupation, and years of clinical experience is stated in Table 2. All participants gave informed consent to the results being used in analysis and publication.

Table 2. Overview of participant demographics.

Participant	Gender	Age [years]	Occupation	Clinical experience [years]
Participant 1	Male	30–39	Ambulance personnel	10
Participant 2	Female	30–39	Ambulance personnel	10
Participant 3	Male	30–39	Medical doctor	6
Participant 4	Male	21–29	Ambulance personnel	2
Participant 5	Female	21–29	Ambulance personnel	1
Participant 6	Female	21–29	Ambulance personnel	1
Participant 7	Male	21–29	Ambulance personnel	1
Participant 8	Male	21–29	Student/ambulance	1
Participant 9	Male	21–29	EMT	7
Participant 10	Female	21–29	Student/ambulance	5
Participant 11	Male	21–29	Student/ambulance	1
Participant 12	Male	21–29	Student/ambulance	2

Testing protocol

Using the neck prototype (*iteration 3)* previously described, the participants performed three tests to evaluate the prototype during trauma scenarios, its validity, and realism. The testing protocol consisted of:

- Simulation of trauma scenario requiring spinal immobilization.
- Free interaction with the prototype for feedback.
- Post-test questionnaire and Likert scale.

Trauma scenario simulation

The participants were introduced to a simulated scenario where an unconscious patient was lying on the ground wearing a ski helmet, as shown in Figure 4. It was emphasized the objective was to immobilize the neck to prevent further spinal injuries. In pairs, they were asked to:

1. Remove the ski-helmet.
2. Immobilize the patient.
3. Perform a lift to transfer the patient to a bed placed a couple of metres away.

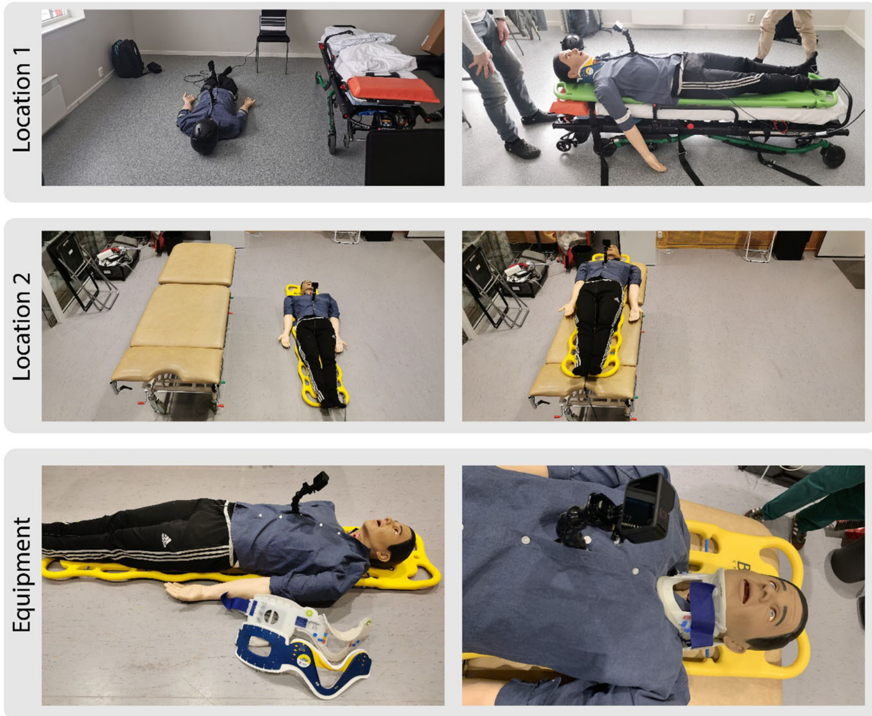

Figure 4. The locations used for the user experiments and the utilized equipment for performing spinal immobilization and patient transfer.

This procedure was performed twice. Firstly, it was done without any aiding equipment, with full manual immobilization during the lift. Secondly, the participants were required to use a backboard and a cervical collar. The aim was to gather quantitative data from the sensors to evaluate the quality and resolution obtained given the different scenarios. A camera mounted on the mannequin torso, also recorded the handling of the head to be able to compare it to the movement measured by the sensors. User tests 1–5 were performed at location 2, and user test 6 was performed at location 1, shown in Figure 4.

Free interaction with the prototype

The participants were asked to freely interact with the neck and compare the movement to an unconscious patient in terms of the range of motion and tactile experience. Feedback was gathered through free dialogue while participants interacted with the prototype. The aim was to obtain insights on the viability of the prototype in trauma simulations, and the realism of the prototype's tactility and range of motion.

Questionnaire

All participants filled out a questionnaire, collecting demographical information and years of clinical experience. A Likert scale was part of the form, consisting of five statements the participants rated from 1 to 5, where numbers one to five meant 'Strongly disagree', 'Disagree', 'Neutral', 'Agree', and 'Strongly Agree', respectively. The questionnaire gathered feedback concerning specific aspects of the prototype by the statements listed below:

1. The neck feels like an unconscious patient's neck.
2. The patient lift from the ground to the stretcher felt realistic.
3. The weight (of the head) feels realistic.
4. The looseness of the neck feels realistic.
5. The range of motion of the neck feels realistic.

MotionScore

There is a lack of benchmarks and/or established formulations of how much (and what) movement is considered critical during handling of patients with spinal injuries (Swartz et al. 2018). Therefore, we utilize an assumption that large deviations from a stable and neutral position, are worse than keeping the head still (which is the formal instruction for handling patients with traumatic neck injuries). A score for evaluating relative movement during testing was derived based on this assumption, called the MotionScore (MS). Scoring of head movement has also been utilized in other studies such as (Nolte et al. 2021), which proposed a similar metric to measure the relative angle between the torso and the head. The equation for calculating the MotionScore is given in Equation 1. The angular motion, denoted as ω and given in degrees, is the sum of the angular motion in the frontal direction, sagittal direction, rotation, and tilting of the head, at a given moment during the simulation. The angular motion can be used to evaluate the neck's relative movement over time by summing up the angular motion at each time-point, obtaining ω_{tot}, dividing it by the length of the interval in seconds, and multiplying it by 0.01 [sec/degree]. The result is the MotionScore, a dimensionless value that represents the area underneath the displacement-time graphs obtained during simulated events.

$$MS = \frac{\omega_{tot}}{t} \times 0.01 \quad \text{MotionScore (MS)} \tag{1}$$

Momentaneous spine deviation (MSD)

To detect and analyze sudden and large movement of the neck during simulations, a performance metric was developed, hereafter referred to as the momentaneous spinal deviation, or MSD. This metric considers the distance between the top of the spine and the natural axis of the neck. We utilize the distance conversion factor of the spring displacements, ending up with the spinal deviation throughout the simulation. The time-derivative of the resulting distance-time graph provides the momentaneous spinal deviation at each point in time during simulation events.

Results

Sensor raw data

To visualize the objective data recorded from the simulations we look at the tracked angles along the timeline of the event. As an example, we have plotted the results from user test 6 showing both testing conditions of the scenario, being patient handling and transport with and without equipment. Furthermore, in addition to the data from both conditions, we have extracted descriptive still frames from the camera pointing at the mannequin face. The frames are correlated to events of interest throughout the scenario, and the timing is indicated where the event appear on the graph. The events for the no use of equipment condition are the start position for the simulation, the removal of the ski helmet, a 'fork-grip' supporting the head and lifting the back, the patient lift, releasing the patient from the 'fork-grip', and the end position of the simulation. The same procedure was done for the condition requiring the participants to utilize a cervical collar and a backboard. The events mapped from the still frames are the start position of the simulation, the removal of the ski helmet, applying the cervical collar, log-rolling the patient onto the backboard, the patient lift, and the end position of the simulation. The recorded data, event frames, and mapping of events onto the graphs is shown in Figure 5.

Likert Scale results and feedback from free interaction discussion

From the questionnaire, the results of the Likert Scale are presented in Table 3. The table shows the averages and standard deviations of the twelve participants' ratings on the Likert scale.

From freely handling and examining the functionality of the prototypes the participants provided feedback and comments. These are presented below in the form of quoted comments, and summarized findings obtained from general discussions surrounding the presented simulator concept:

- '[…] when patients are unconscious, and the muscles are relaxed, the head and neck are really loose, looser and more flexible than people think. This neck captures this aspect well.'
- '[…] remarkably better than the other simulators we have used.'

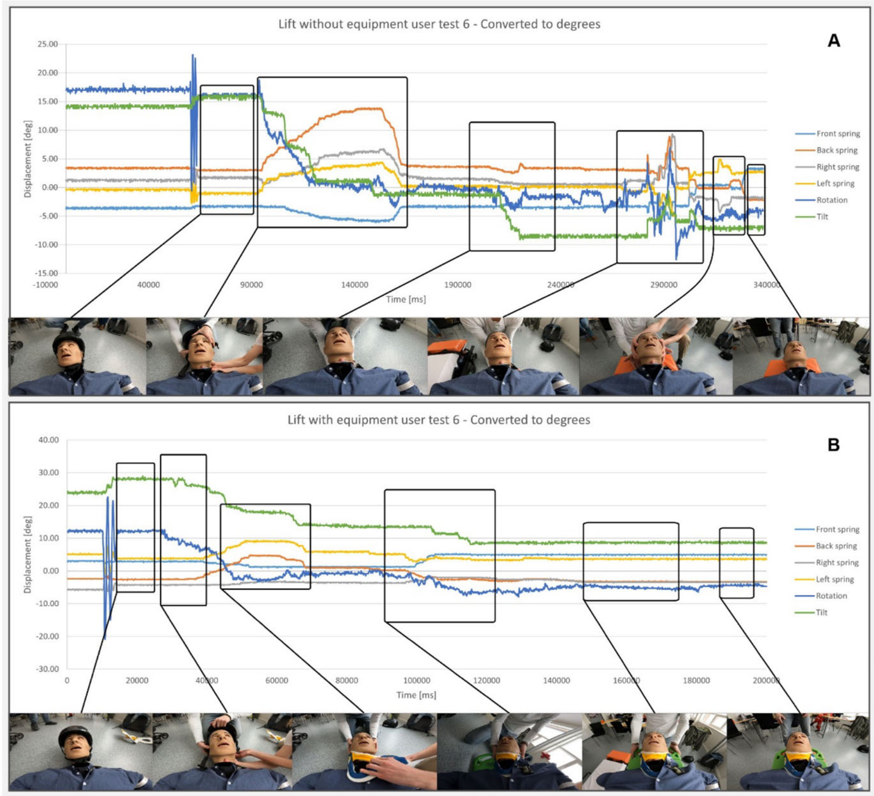

Figure 5. Recorded movement plotted from user test 6 in both without (A) and with (B) equipment conditions. Still frames are synchronized, and boxes are superimposed onto the relevant graph sections.

Table 3. Average results from the questionnaire, $n = 12$.

Question	Statement	Average rating	SD
1	The neck feels like an unconscious patient's neck	3.83	0.69
2	The patient lift from the ground to the stretcher felt realistic	2.42	1.04
3	The weight (of the head) feels realistic	3.42	1.19
4	The looseness of the neck feels realistic	3.92	1.11
5	The range of motion of the neck feels realistic	3.83	0.90

- 'It feels like it is missing an aspect of the natural resistance from the muscles in the neck.'
- 'The largest flexion is a bit too large.'
- 'The head falls naturally to the sides as it would with a real patient.'

It was stated that the status of patients is only measured properly from arrival at the hospital; pre-hospital stabilization is not scored or measured well currently. The potential of measuring how different immobilization techniques affect the neck in the pre-hospital scenarios was interesting and desirable. The body (meaning torso, arms, and legs) affects the neck more than it would in a real trauma scenario, due to the torso being too stiff.

Feedback and performance metrics

The ability to provide objective feedback during simulation of dextrous procedures is important, as this could enhance psychomotor skills from repeatedly performing procedures correctly. In suspected spinal injuries, it is important to keep the spine as still as possible. even though a specific limit for motion leading to further damage to the spine currently does not exist (Swartz et al. 2018; Gerling et al. 2000). Hence, large and sudden movements are undesirable and should be avoided during spinal immobilization, and handling. The momentaneous spinal deviation (MSD) metric is applicable to highlight such movements during simulation scenarios. This is exemplified by looking at both the testing conditions of user test 1. Large and sudden movements of the head are identifiable by applying the MSD, and both the magnitude and timing of the sudden movements are shown in Figure 6.

As there does not exist any threshold for an MSD value where further damage to the spine is likely (Gerling et al. 2000), the threshold can be set dynamically to vary the difficulty and scope of the exercise depending on the scenario or experience level of the trainee. An example of an MSD threshold of ±0.3 mm/sec applied to the recording of user test 4 without equipment is shown in Figure 7.

The participants in user test 4 exceeded the set threshold at 74, 104, and 107 seconds into the simulation. By retrieving a pair of still frames from these moments, the causality could be investigated. For the moments investigated in this test, the movements exceeding the threshold can be linked to the events of removing the ski-helmet (74 sec.), beginning of patient lift

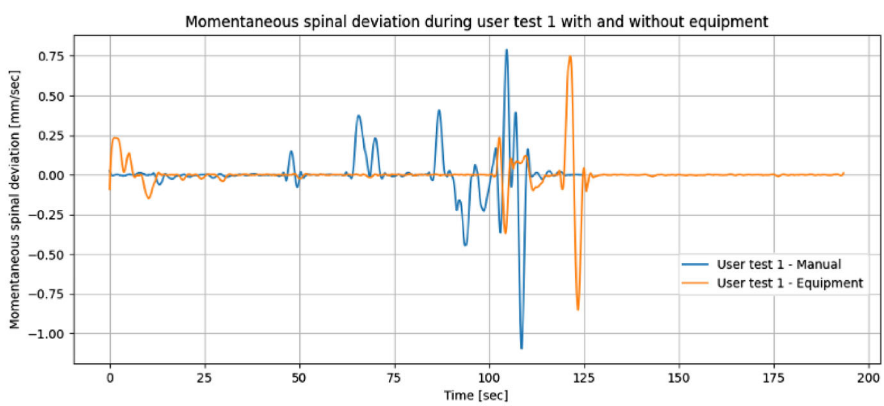

Figure 6. MSD of user test 1, with and without equipment.

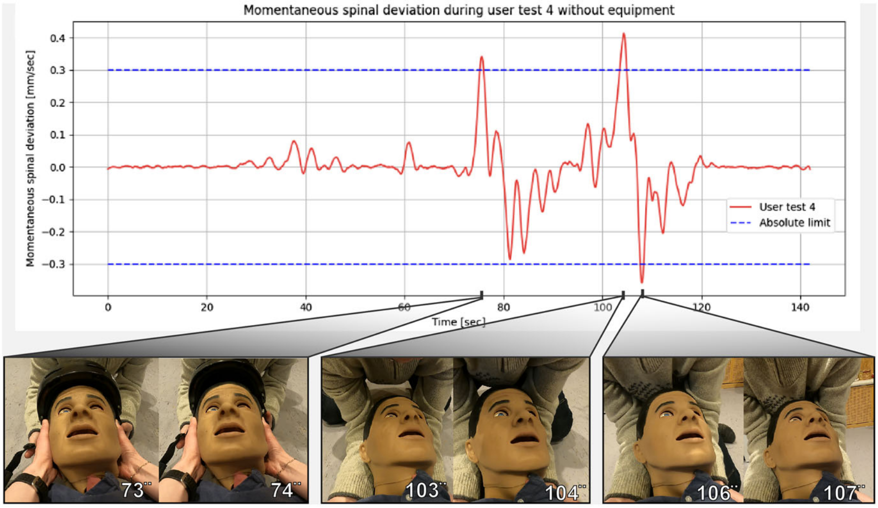

Figure 7. MSD of user test 4 without equipment, with a threshold set to ±0.3 mm/sec. Still frames from the events occurring when the threshold is exceeded are superimposed.

(104 sec.) and during lift (107 sec.). The MSD for all the tests both using and without using aiding equipment are shown in Figure 8.

Debrief and quality metrics

Using the MotionScore previously established, the six user tests can be analyzed and presented. During testing, however, the front spring malfunctioned and did not provide correct readings from user test 2 and onwards. The MotionScore for the rest of the user-tests disregards the front spring and considers the back spring instead, as it is the inverse of the front spring for a certain deflection range (within limits of what the prototype experiences during immobilization and careful handling).

To compare the neck movement between each user test, the MotionScore-analysis starts when the participants have positioned the mannequin to look straight forward with the helmet on. The analysis ends after the mannequin has been transported to the stretcher at rest. Using no equipment, user-test 1 registered an MS of 5.58. Meanwhile, the MS was 3.18 when a backboard and cervical collar were utilized. The MotionScore for each test is listed in Table 4, along with the mean angular deviation and standard deviation.

Discussion

Viability of the prototype

For users to leverage simulation-based training to transfer learning into clinical scenarios, simulators need to be sufficiently realistic. The results from the

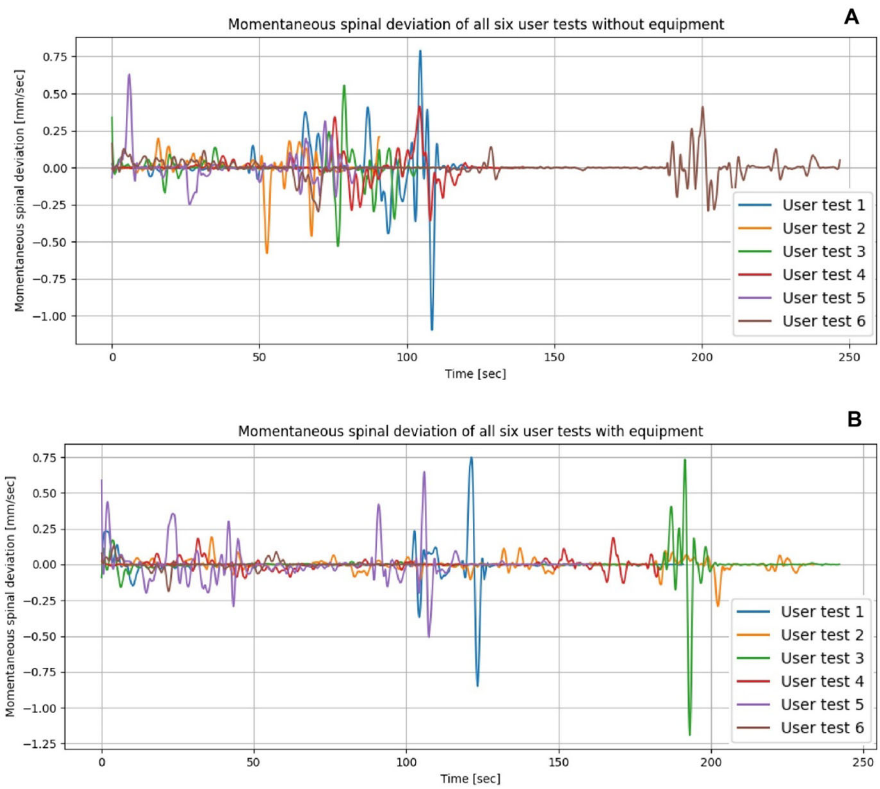

Figure 8. The MSD of all six user tests. Figure A shows the tests performed with equipment and B shows the tests performed without equipment.

Table 4. MotionScore and mean angular deviation and standard deviation of the tracked simulation events.

	MotionScore		Mean angular deviation and standard deviation	
User-test #	Without cervical collar and backboard	With cervical collar and backboard	Without cervical collar and backboard	With cervical collar and backboard
1	5.58	3.18	30.74 (8.67)	17.51 (4.70)
2	8.40	3.03	46.19 (10.40)	16.66 (7.09)
3	5.67	2.17	31.21 (15.80)	11.93 (6.84)
4	3.62	3.60	19.91 (7.68)	19.80 (8.19)
5	4.95	2.42	27.23 (9.63)	13.29 (8.72)
6	2.84	2.19	15.60 (6.42)	12.07 (3.23)

Likert scale and feedback during the free interaction point out apparent limitations of the current prototype. Aspects of the prototype did not facilitate realistic motion when lifting the patient as the results from statement 2 on the Likert scale clearly show. Pointed out was the torso, arms and legs, being both rigid and light compared to real patient. The torso was also anatomically incorrect, making the interaction less realistic. This furthermore led to the cervical collar not having a defined collar bone to rest against, thus affecting the support it provided the head. It was also noted the neck did not feel as naturally resistant to rotation, which is most likely due to the neck not being supported by tissue and compliant structures other than the spine and windpipe.

In terms of feedback concerning the included functionality of the neck prototype, the overall results were positive. Concerning the compliance and range of motion of the neck, it was considered adequate to what they would expect from a real patient. This corresponds well with the results from the Likert Scale, where these statements scored highly. The range of flexion was described as too large, and while the range should be adjusted, this does not affect the results from the experiment where the aim was to restrict the motion as much as possible. Hence, we see the presented prototype as a viable application in emergency care training of spinal injuries and should be developed further.

Possibilities for evaluating and comparing performance

Reviewing the obtained sensor data from the experiments, the spine's position, orientation, and the head's rotation could be further utilized depending on the objectives of the training scenario. The two metrics proposed in this study could enable trainees to get objective feedback on performance in pre-hospital immobilization and transportation training. This area of trauma care does not currently have any measurable parameters except for retrospective studies comparing the mortality and paralysis rates of real patients. Thus, having the opportunity to investigate simulated interventions through objective measures such as the movement data described in this paper could be of great value, also for evaluating and determining best practice.

The momentaneous spinal deviation introduces a direct and quantifiable performance metric for feedback during the interaction, and analysis of the event for debrief purposes. While the least amount of sudden and large motion of the neck to exacerbate spinal injuries is not known, it is argued that the general standard should be as little movement as possible (Gerling et al. 2000; Swartz et al. 2018). The MSD values shown in this paper are applicable for measuring the amount of relative motion a simulated patient endures during simulation. Hence, a threshold for allowed motion in training scenarios could be determined empirically by further research using the presented concept. By obtaining a large data set from highly skilled medical personnel, a threshold for acceptable relative motion of the head could be determined. This could enable a feedback response (audible, visual, or verbal) to be given trainees if the allowed threshold is exceeded. Such a threshold could, moreover, be tailored to specific trauma scenarios, patient characteristics, or the skill level of the participants. Hence, objective feedback and tailored training for managing spinal injuries could be enabled.

The suggested performance metric MotionScore, enables comparisons between entire immobilization and transportation scenarios. Like the MSD, a MS threshold for excessive motion is not defined as a result of lacking empirical data and clinical standards. However, in this study, the MS has been used to capture the difference between performing spinal immobilization with and without aiding equipment with regards to limiting relative head motion. The participants were not asked to perform the immobilization to be evaluated on their performance. Thus, the results presented for the user-test are not valid for evaluating the use of cervical collars and backboards compared to manual handling. The results do, however, call for further investigation as they all suggest a difference favouring the use of aiding equipment, but only in terms of limiting the movement of the spine and head.

Even though the data collected from the prototype could be used as valuable performance indicators in both formative and summative feedback, it can only describe the prototype's motion (McGaghie et al. 2010). The prototype does not capture the external factors of the interaction between the trainee and simulator, like the number of people partaking in the simulation and the techniques used. The performance indicators must be applied in a way that reflects the simulation case and the relevant learning objectives (Issenberg et al. 2005). This calls for further research on the implications of utilizing the concept in medical training, learning outcome, and simulated events.

On leveraging sensor data

From visual inspection, the sensor data clearly indicate parameters describing actions performed by participants. Not restricted to the case of spinal immobilization, the angular motion of the spine can be leveraged for a broad range of use-cases. For example, exploring how users position the head during simulated patient interactions could be further investigated. An example could be airway management training, where the users can get direct feedback on how the tilt and position of head correlate to an ideal position ensuring free airways.

Further exploration should also include better feedback during trauma scenario simulations, where there is currently a lack of objective measurements. Both the pre-hospital patient treatment and patient transportation to the hospital could benefit from measuring how different techniques and procedures affect the spine of the patients in terms of the motion it endures. Hence, the results presented in this study is merely a snapshot of the possibilities. Further research concerning medical validity is however required, but we suggest the concept described in this paper as a potential tool to facilitate such studies.

Insights on developing patient simulators

The development and testing of the prototype described in this study has shown the importance of purposeful involvement of experienced users at various stages of the project. For a patient simulator to be applicable in medical training, the functionality, fidelity, and clinical realism should be collectively sufficient to facilitate relevant and realistic interactions. To ensure the simulator correlates with these aspects, the users have been involved at critical junctions throughout the development process. To maximize learning from interactions with users, they should be made to target specific aspects of prototypes, by addressing specific design questions. This is exemplified by prototyped functionality, interactions, look or feel, and how these aspects could be improved. This presupposes the prototypes are made with the right intent and audience in mind. A prototype in the early product development phase should define itself as a potential answer to a question related to how the final product should perform. Thus, a user can be presented with the prototype and validate whether the function or behaviour etc., is correct or not and explain why. This interaction either validates the solution prototyped or provides valuable insight the developer often would not be able to acquire independently or as quickly.

The development of medical simulators, where there is often a substantial knowledge gap on the developer's part, can benefit from utilizing the insights mentioned earlier regarding continuous user-involvement to ensure the final product aligns with the user-needs and requirements.

Conclusion

This paper has presented the development and testing of a new neck concept for human patient simulators to be used in trauma scenario training. Shortcomings in current patient simulators and the importance of training for suspected spinal injury scenarios have been identified. Training for these scenarios using simulation, the treatment and immobilization of the neck are important aspects to consider. Especially since the current solutions lack the realistic range of motion, compliance, and objective performance indicators for improving training and facilitating learning.

The team deployed an iterative and prototype-driven development approach by relying on frequent consultations with users. This enabled the solutions to align with users' expectations and experience of handling an unconscious patient, as well as probing the needs for a solution to fit medical guidelines and current curricula. A proposed concept aims to replicate the behaviour of the neck of an unconscious patient by mimicking the human anatomy and vertebrae. By utilizing several sensors, the prototype also measures the relative motion it is subjected to during interventions and handling.

By performing experimental user-tests with medical professionals and students ($n = 12$), the interactions and handling of the prototype have been assessed qualitatively and quantitatively. The conceptual neck was rated by the participants to be a good representation of an unconscious patient's neck in terms of the looseness of the head and the range of motion during handling. Furthermore, the recorded motion of the spine and head during the simulations have been used to suggest performance metrics assessing the quality of handling and provide corrective feedback during the simulations. The generated data is analyzed and discussed as potential quality performance indicators for both formative and summative feedback in simulation-based trauma training.

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