“What’s Happening at that Hip?”: Evaluating an On-body Projection based Augmented Reality System for Physiotherapy Classroom

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ABSTRACT

We present two studies to discuss the design, usability analysis, and educational outcome resulting from our system *Augmented Body* in physiotherapy classroom. We build on prior user-centric design work that investigates existing teaching methods and discuss opportunities for intervention. We present the design and implementation of a hybrid system for physiotherapy education combining an on-body projection based virtual anatomy supplemented by pen-based tablets to create real-time annotations. We conducted a usability evaluation of this system, comparing with projection only and traditional teaching conditions. Finally, we focus on a comparative study to evaluate learning outcome among students in actual classroom settings. Our studies showed increased usage of visual representation techniques in students’ note taking behavior and statistically significant improvement in some learning aspects. We discuss challenges for designing augmented reality systems for education, including minimizing attention split, addressing text-entry issues, and digital annotations on a moving physical body.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in HCI**; *Usability testing*; Field studies.

KEYWORDS

Augmented reality, pen-based interactions, annotation, projection mapping, educational system.

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1 INTRODUCTION

Augmented reality (AR) systems have been adopted as a powerful tool to enhance the teaching and learning experience in many classrooms. AR systems overlay virtual information directly on the physical world, offering great potential to improve training and educational outcomes [6, 20, 25]. These systems often leverage virtual 3D visualizations to make difficult ideas more comprehensible [25]. They can transform the physical space into interactive venues, where otherwise inaccessible digital information can be observed and analyzed [6]. AR visualization in instructional settings can also improve task completion times and lead to fewer errors [20].

While providing a novel visualization capability through overlaying digital information with real world artifacts, these systems typically prioritize display capability rather than interactivity. A systematic review of AR trends in education [3] shows that the majority of AR educational systems focus on visualization by aiming to “*augment information*” (40.6%) and/or “*explain a topic*” (43.7%), as compared to support “*lab experiments*” (12.5%) or “*exploration*” (3.13%) where interactions with the contents are encouraged.

Billinghurst et al. [4] outline the promise of *hybrid user interfaces* [7] that combine AR with other interactive technologies such as virtual reality (VR) and pen-based devices.

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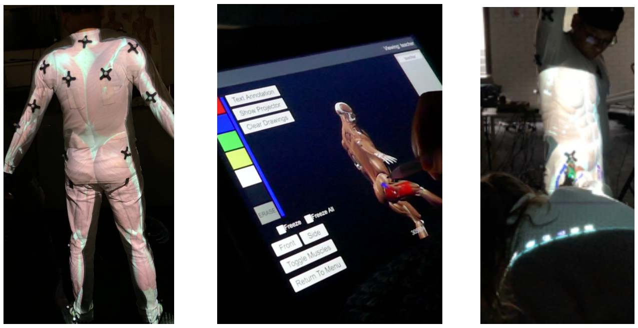


(a) (b) (c)

Figure 1: *Augmented Body* system for physiotherapy education - (a) projection mapping on a student's body, (b) pen-based tablet interface for annotation, and (c) pen-based selection/drawing on the physical body.

This approach presents complex challenges and difficulties in balancing synchronized combination of multiple interaction modalities, especially in AR systems where the user is engaged in multiple senses (e.g., visual, haptic, and proprioception) [23]. Such multimodal integration may require the user to juggle between the temporal dimension of multiple modalities: some provides discrete inputs (e.g., gesture) while others are continuous (e.g., speech) [22].

A significant concern of AR based educational systems is the imposition of additional cognitive load on learner [6, 17, 20, 23, 25]. AR systems tend to overwhelm learners with extraneous information and push them towards their limits for information processing capacity [20]. Learning tasks that have been remodeled through AR can be overly complicated. These factors led to the rise of cognitive load demands in AR educational systems. One potential approach is using pen-based interaction mechanism that builds upon existing writing skills and spatial cognitive processes, thus potentially reducing cognitive load in learning environments [18]. However, an analysis of integrating pen-based interactions with projection-based AR educational systems in missing – both in terms of usability and educational outcomes. We need to understand which interactional aspects work (or not) and how these multimodal interactive technologies influence learning outcome and experience in real-world settings.

In this paper, we present the development and evaluation of *Augmented Body* (AB) – an AR based educational system for physiotherapy classrooms that supports interactive contents authoring through pen-based interactions and projection mapping (Figure 1). This AR system projects virtual skeletal and muscular models on a body and uses pen-based interactions to achieve two goals: (i) enable active participation of the students and teachers in authoring and interacting with content; and (ii) support note taking with individual pen-based annotation and text notes. This paper reports on a usability evaluation of the developed AR/pen-based system and in situ evaluation of educational outcome in real-world settings. The evaluation consisted of cognitive load NASA-TLX [10], Mental Rotation Test [24], written exam, as well as subjective measures of usability and experience through participant interviews and observations. The system was integrated into an academic curriculum and deployed with a cohort of 101 students to evaluate educational outcomes.

The paper makes the following contributions: (i) We present an understanding of the usability issues of a hybrid AR system for physiotherapy education, (ii)We present usability analysis and educational outcome evaluation of the full working system comparing between three conditions (projection with tablet interface, projection only, and traditional teaching), and (iii) We discusses the potential scope for educational outcome by comparing traditional learning with the usage of the developed prototype.

2 RELATED WORK

Usability Challenges of AR Educational Systems

A recent systematic review on AR usage in education [1] has revealed that besides the positive pedagogical outcomes (e.g., increased motivation, collaboration and interaction in the classroom, etc.), AR technologies bring multiple challenges for the students. Usability difficulties, increased cognitive demands, and distraction are among the long list of issues when applying AR in the classroom. Radu [20] conducted a meta review comparing AR-based educational systems with learning through other approaches. The review stressed the usability challenges imposed by AR based learning technologies. AR technologies can cause attention tunneling where the students become too focused on the tool and ignore the broader pedagogical goals. The issue of cognitive load is particularly troublesome as discussed in the survey by Wu et al. [25] and literature review by Dunleavy and Dede [6]. They highlighted that the quantity of information and the unfamiliarity with the AR technologies are principle contributors to cognitive load. In addition, Bacca et al. [3] highlights the need for new interaction methods that enable teachers and students to create 3D/AR content. Suggested solutions to these usability issues include simplifying the experience, limiting the number of virtual artefacts, and providing scaffolding to guide the students through the learning experience [6].

Interactive AR Educational System

Hoang et al. [11] developed *Augmented Studio* (AS) that uses body tracking to project anatomical structures and annotations (in Wizard of Oz approach) over moving bodies for physiotherapy education and demonstrated the potential of AS in a pilot study. However, AS does not have the capability for interaction with the virtual anatomy. We built upon this work and developed a pen-based tablet interface (Figure 1(b)) as an interaction mechanism alongside the projection mapping system to create a hybrid user interface. We identified usability issues with the tablet interface and developed a 3D printed pen with trackers to enable drawing directly on the projection surface (Figure 1(c)). In this paper, we investigate how such hybrid system perform in real-world settings.

Hybrid User Interfaces. Feiner and Sharmash [7] first described the concept of hybrid user interfaces by combining display and tracking technologies. Bornik et al. [5] extend this by leveraging virtual reality for its 3D visualization capability, tablet devices for their high resolution display, and touch screen input to create a hybrid transition between 3D and 2D content. Mandalika et al. [15] proposed a similar hybrid combination using desktop VR and pen-based tablet for radiologists performing diagnostic tasks on 3D medical imaging. Their evaluation shows an increased performance in task completion time and accuracy for the hybrid system as compared to a 2D interface. However, task load NASA score [10] is higher using hybrid interface versus 2D.

However, none of these hybrid systems allow users to take advantages of the multiple available technologies simultaneously, as the use of one (e.g., VR) precluded the use of the other (e.g., Tablet). Also, as the number of students increases, it is very difficult to scale, due to the high cost of VR and associated technologies. In our AR educational system, we focus on using existing and familiar input device (e.g., stylus, 3D printed pen, tablet devices, etc.) to reduce the complexity and learning requirement for teachers and students.

Pen-based Annotation. Gorgan et al. [9] outline three types of pen-based annotations for medical education: annotations on a document, annotations in 2D over 3D objects, and annotations in 3D over 3D objects. The first two methods only work for a purely virtual environment, where annotations can be displayed in midair. A projection mapping system can only display annotation over 3D object, as it requires a physical projection surface. Therefore, for the companion tablet interface, we only enable hand drawing annotation on the avatar (Figure 2(c)), which was then projected on the human model.

Virtual annotations on the human body is a common approach in AR for medical and surgical training. Andersen et al. [2] built an AR simulated transparent display for surgical training. A remote mentor can create, position, orient and size virtual annotations, which are displayed on a tablet device positioned above a humanoid manikin for the mentee. The tablet renders the virtual annotations, including shapes, surgical tools, labels, and hand gesture icons, as an overlay on a video stream of the manikin underneath. A pilot study demonstrated that the AR system improves accuracy in surgical tasks while also called for improvements towards perfect alignment of virtual annotation on the image frame.

3 RESEARCH DESIGN

Inspired by these works, we leveraged the benefits of hybrid user interfaces using pen-based tablet and motion tracking to tackle the usability challenges of AR educational systems (study 1) and evaluated the learning outcome (study 2). Study 1 focused on developing a fully working system to resolve usability issues through a classroom deployment (voluntary participation). We compared three different conditions - traditional classroom (Tr), on-body projection (Pr), and projection with tablet (Ta) interface to investigate their relative advantages and implications. In study 2, we took our learnings to further develop and refine the *Augmented Body* system and integrated it as a part of the regular curriculum for short duration. The objective in study 2 was to evaluate learning outcome and identify implications for future research.

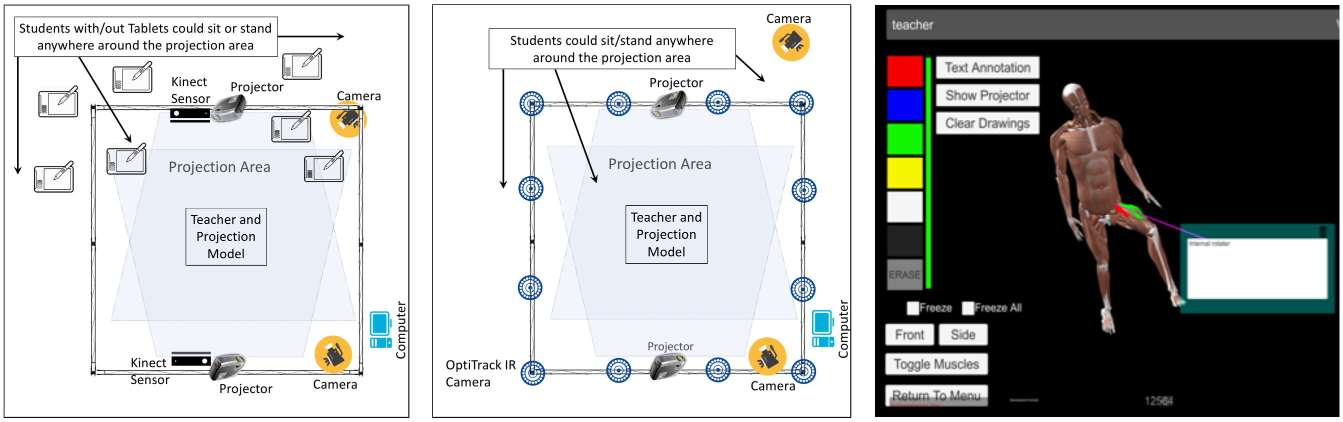
In both study 1 and study 2, we used SPSS to make quantitative analysis of the word count (paper notes), MRT (Study 2), NASA-LTX (Study 1), and written test scores. We analyzed all the video recorded observations with the help of the teacher and transcribed all the focus group discussions and interviews. All these data were coded and we performed inductive thematic analysis on the qualitative data using NVivo 11 to identify recurring themes as well as unique practices.

4 STUDY 1: *AUGMENTED BODY* SYSTEM WITH PROJECTOR, KINECT SENSOR, AND TABLET INTERFACE

Study 1 Implementation

We implemented the *Augmented Body* system using two projector and Kinect sensor pairs, facing each other. We created a tracking area of 3x3x3*m*, made up of four tripods connected with cross beams in a physiotherapy classroom (Figure 2(a)). We performed calibration using the Microsoft RoomAlive toolkit [13] to map the topography of the classroom and to enable projection mapping. We combined this with body tracking using Kinect sensor, resulting in the ability to project a virtual anatomy model onto a moving body in the tracking space (similar to Figure 1(a)). We purchased a skeletal and muscular virtual model and verified its anatomical correctness with staff members from the Physiotherapy Department.

We built a network infrastructure using Unity3D game engine and its multiplayer platform to send Kinect tracking data to a server for distributing to multiple tablet devices. We also built a Universal Windows Platform application to run on Microsoft Surface Pro 3 devices with digitizer stylus input. The tablets were connected to the local Unity3D server to



(a) (b) (c)

Figure 2: Schematic diagram of the setup and tablet interface (a) Study one setup, (b) Study two setup, and (c) Hand drawing annotations (green and red strokes on the upper thigh) and text annotation (green window) in the tablet device.

visualize the movements of the 3D anatomy model in real-time (Figure 2(c)). Hence, effectively each tablet is a virtual environment that duplicates the movement of the student volunteer in the projection space.

The teacher and students could draw colored annotations directly on the virtual body shown in the tablet screen using the associated stylus (Figure 1(b)). Each drawing stroke is sent to the Unity3D server and rendered in real time on the physical body of a volunteer student in the projection space. The teacher could also choose to project annotations by any particular student directly on the volunteer and provide immediate feedback to the class. Students could use their tablet to navigate the virtual environment via pan and zoom using multi-touch gestures. This allowed the student to view the virtual model volumetrically. Students could attach textual annotation to any certain joint or muscle on the body using their tablet device (Figure 2(c)). Thus, the tablet interface acted as a mechanism to capture, augment, and enhance the learning experience for the students by allowing to create their own personal notes and annotations.

Interactions in the projection area was captured live to the virtual environment on the tablet, including the volunteer's movements as well as the teacher's drawings and annotations. A database server was set up to store movement data, voice recording of the lesson, and annotations of the students and the teacher – allowing students to review the class along with their personal annotations and notes later on.

Study 1 Deployment and Usability Analysis of Augmented Body System

Prior to this study, we conducted a user centric design process with students and teachers at the Physiotherapy Department. We verified a conceptual design of projection mapping based system for physiotherapy teaching through a high-fidelity prototype [11] and progressed towards developing a complete system. We revealed that students learn anatomy in various ways, e.g., dissecting cadavers, skeletons, anatomy posters, hand drawings as well as practicing on each other's body, etc. However, our focus group discussions indicated that they often struggle to translate anatomical understanding onto the patient's body. A main challenge here is understanding the complex inter-relationship among groups of muscles/bones and the amount of information they need memorizing. Students later commented that on body projection assisted them in both learning and replying to the teacher's queries. Further challenges arise from the 3D nature of the actual interactions among muscles and other body parts. Students were unanimous in stating that visualizing the rotations of the muscles are among the hardest problem they face.

During the development of the *Augmented Body* system, we set up weekly meetings with two lecturers from the Physiotherapy Department to discuss requirements, progress, feedbacks, and informal testing. Finally, we conducted a within-subject evaluation study of the developed system.

We recruited 48 physiotherapy graduate students and divided them into 2 groups from first year (14 and 13 participants) and 2 groups from third year (15 and 6 participants); participation was voluntary. Each group participated in three manual therapy sessions (15 minutes each) taught in three different conditions in random order: (1) *Traditional* (Tr) with paper note, (2) *Projection* (Pr) - teacher used a tablet to draw, students took notes in paper, and (3) *Tablet* (Ta) with projection - teacher and each student had a tablet device. We used three movement-teaching scenarios randomly assigned to these three teaching conditions in respective sessions: a tennis forehand swing, a soccer kick, and a skier swing. We hired a student who was not part of the class to demonstrate the movements. The hired student wore white tight clothing, including long sleeve t-shirt and jeans to maximize the visual effect of the projection on body. A teacher familiar with the developed system delivered lectures in all sessions. The annotation tasks were identical between different groups of students with same movement-teaching scenarios. Each session followed the same structure where the teacher assisted the students in understanding the joint movements, actions of muscles and gravity, the speed of movements, and other specific components such as balancing and stabilizing actions.

We asked the participants to take notes to help them understand the content and to assist them in revisions. We provided blank paper in the *traditional* and *projection* conditions and a Microsoft Surface Pro tablet with a digital stylus for the *tablet* condition along with a training time before the session. After each session, the students completed a NASA-TLX (Task Load Index) questionnaire [10] and open ended comment to measure the subjective mental workload, based on six dimensions: *mental demand*, *physical demand*, *temporal demand*, *performance*, *effort*, and *frustration level*. Each dimension was indicated on a visual analog scale, to be converted to numeric values, from 0 indicating low effort to 100 for high effort.

We arranged one follow up session with each group of participants (22 attended) one week after the lessons where they completed a short written-test related to the content covered (marked by an external tutor from Physiotherapy Department). We also conducted a short interview with the participants to understand how they used the projection and tablet systems during the sessions.

Study 1 Data Collection

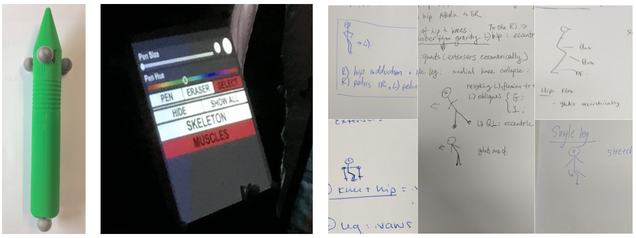
We collected (i) video recorded data of all the teaching and follow up sessions, (ii) three NASA TLX questionnaire responses from each participant for the three conditions, (iii) any paper notes students made during the teaching sessions, (iv) screen recordings with audio from each student's tablet, and (v) audio recorded interview data.

5 STUDY 1 FINDINGS: USABILITY ANALYSIS OF *AUGMENTED BODY* SYSTEM

We begin with presenting usability related issues and comparison between the three teaching conditions in study 1. Then, we take the lessons to refine *Augmented Body* for study 2 and report its impact on learning outcome.

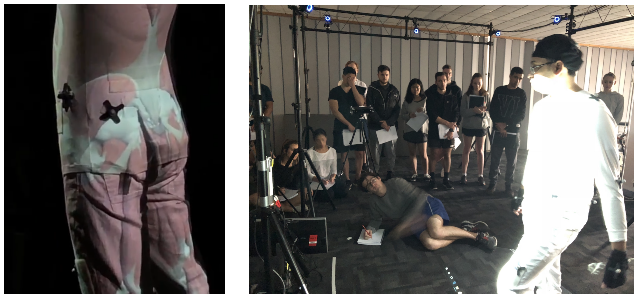
Task Load Analysis

We tested the NASA-TLX questionnaire data for normality and all of the six dimensions failed (Shapiro-Wilk test, $p < 0.05$). Therefore, we ran the non-parametric Kruskal-Wallis H test and found a significant result in all dimensions - mental demand: $H = 18.75, p < .001$; physical effort: $H = 11.37$, $p < .01$; temporal demand: $H = 24.71, p < .001$; effort: $H = 26.18, p < .001$; performance: $H = 16.90, p < .001$; frustration: $H = 31.70, p < .001$.



(a) (b) (c)

Figure 3: (a) 3D printed pen, (b) Projected palette, and (c) Sample of notes taken during projection-based classes.



(a) (b)

Figure 4: (a) Teacher could remove upper layer to reveal inner layer of muscles and bones, (b) Part of the classroom.

We performed a post-hoc Mann-Whitney U tests between the conditions. We were not testing for a universal null hypothesis across all conditions; therefore, a Bonferroni correction was not applied [19]. Our data (Table 1) showed that projection (Pr) condition exerts significantly less *mental effort* as compared to traditional teaching (Tr) condition $U = 901, p = 0.03$ and tablet (Ta) condition $U = 566, p < 0.001$. Also, there is a significant difference between traditional and tablet condition $U = 810, p = 0.006$. Similarly, both projection and traditional conditions exerts significantly less *physical effort* than the tablet condition, $U = 863, p = 0.01$ and $U = 699, p < 0.001$, respectively. Projection condition also causes significantly less *temporal demand* on the students, as compared to the traditional $U = 679, p < 0.001$ and tablet conditions $U = 498, p < 0.001$. The projection condition causes significantly less *effort* than tradition teaching condition $U = 783, p = 0.003$ and tablet condition $U = 484, p < 0.001$. The traditional

Table 1: Average (Avg.) and standard deviation (Std.) for measures across six indicators of cognitive load. For performance, higher value is better outcome. For all other dimensions, lower value is better outcome.

Task Load Index Dimensions	Conditions						Significant Differences
	Traditional (TR)		Projection only (PR)		Tablet (Ta)		
	Avg.	Std.	Avg.	Std.	Avg.	Std.	
Mental Effort	53.5	30.1	42.4	27.9	68.1	26.7	Pr<Tr<Ta
Physical Effort	22.9	25.9	30.4	26.4	43.0	32.9	(Pr,Tr)<Ta
Temporal Demand	62.2	29.5	40.9	28.7	70.7	26.8	Pr<(Tr,Ta)
Effort	58.7	27.3	43.3	27.5	73.0	27.2	Pr<Tr<Ta
Subjective Performance	50.3	34.1	41.2	29.5	25.4	32.3	(Pr,Tr)>Ta
Frustration	35.6	28.5	31.6	26.6	69.4	33.3	(Pr,Tr)<Ta

condition also causes less *effort* than the tablet condition $U = 764, p = 0.002$.

For *subjective performance*, both the projection condition and traditional condition performed better than the tablet condition, $U = 767$, $p = 0.002$ and $U = 607, p < 0.001$ respectively. There was no significant difference between the projection and traditional conditions. The students rated significantly higher *frustration* with the tablet condition as compared to traditional $U = 519, p < 0.001$ and projection conditions $U = 461, p < 0.001$. We ran a single factor ANOVA analysis on the score of the short test (passed Shapiro-Wilk test for normality, $p > 0.05$), but it did not show any significant difference among the three conditions. We examine learning outcome in details in study 2.

To summarize, projection condition (Pr) showed significantly better performance in every cognitive load dimension compared to both traditional (Tr) and tablet (Ta) condition. The underperformance of the tablet condition in terms of cognitive load was unexpected; we interrogated this result through the interviews, which we report below.

Usability Issues with Tablet and Projection Systems

Physiotherapy students have a system of shorthand with standardized abbreviations to describe muscle names, groups, and manual skills, for which the standard Microsoft Windows onscreen keyboard did not suit well. Many of our participants ($n = 10$) explicitly mentioned issues with the autocorrect feature that did not understand common domain-specific abbreviations and caused delays. Students were unable to use the default handwriting recognition system in Microsoft Surface as it also did not understand abbreviations, so they switched to the on-screen keyboard. Some students ($n = 2$) were unfamiliar with typing on an onscreen keyboard and requested a physical one.

Students' use of the tablet interface for text annotations did not conform directly to the paper notebook metaphor, but as a post-it note metaphor instead, i.e., they were expected to create a text annotation by attaching it to a particular point on the body. However, our video analysis has shown some cases where the students just randomly attached the textual description on the body, rather than to the relevant muscle group. The tablet was also considered heavy to be held in one hand for prolonged duration (as students used the stylus or typed with the other hand) and while standing. Many students ($n = 14$) commented that they would prefer longer training sessions with the tablet interface and expected it to perform better with extended usage.

One issue with Projection was that the room was required to be darkened, with lights off and blinds drawn down. Four students commented that the lighting affected their note taking, especially for the projection only condition.

Note Taking

We expected that in traditional condition the students would sketch more to illustrate body movements due to the lack of visual teaching tools. However, the exact opposite happened. Many students drew sketches of stick figures to depict the body movements in the projection condition, while in the traditional class they wrote down textual descriptions of the movement only. A Mann-Whitney U test of word count on paper notes showed that students wrote more words in traditional condition (mean 69 words, SD 47) than projection condition (mean 38.79 words, std 30), $U = 570, p = 0.001$. This behavior showed a progression from verbal description (abstract representation) to sketches and to moving 3D models (more concrete and spatially specific representation) on the continuum of visual presentation [8]. With no augmentation (Tr), students used more textual descriptions of movements; when they had visual aid (Pr), it resulted in more sketches; and when they were presented with moving 3D model on tablet (Ta), it led them to draw directly on that model.

Annotations Usage

Throughout the class in all three conditions, the teacher consistently elicited verbal comments from the students, to identify the part of the skeletal and/or muscular structure that the teacher was lecturing on. Students strongly suggested that having the projection as a visual aid helped them in both understanding the teaching content and in replying to teacher's questions. In the tablet condition, students used drawing in tablet to both take notes and respond to teacher's questions. Video analysis highlighted that the drawing feature was mostly used to color in muscle(s) as a way of identifying the muscle groups that was used for a particular movement (Figure 2(c)). The annotation was used in combination with the ability to switch between skeletal and muscular models. However, there were some instances where the students struggled with annotation on a moving virtual model. The students used a stroking motion with the pen to color in the muscle, only when the model was not in motion. For example, one student immediately lifted the pen and stopped drawing when the virtual model moved. Anticipating this, we implemented the freezing feature, as used in other domains such as video annotation [14]. It was used constantly when the students annotated the muscles.

Annotation was considered the core useful feature of the tablet (9 students explicitly commented), allowing the student to "*visualize the origin of muscle, which could be hard to conceptualize*", and "*highlight the activation of muscle through different phases of the movement*". The annotation layer was rendered on the muscle, thus giving the impression that it stretched with the movements. Students found this feature particularly helpful in understanding the mechanics of the muscle attachment. The ability to attach text note onto the muscle also reduced effort because the student did not have to name the muscle, compared to hand-written notes.

Interaction and Attention Split in Tablet Interface

The tablet interface helped both the students and the teacher to switch between muscular and skeletal views. This visualization style was used both by the teacher on the projection and the students on the tablet to illustrate muscle connections with the skeleton. The students also switched frequently between front and side orthogonal views, both on their own accord and as per instructed by the teacher. During the video review session, the teacher explained that the orthogonal view makes it easier to understand due to similarity with anatomical textbooks. Some students ($n = 9$) found the zoom and rotate features of the tablet visualization helpful. Despite issues with the textual note entry, most of our interviewees ($n = 16$) agreed that the tablet interface has good potentials.

One concern with the tablet interface was that it shifted the attention from the on-body projection and the teacher's interactions with the projection to the tablet interface. In the interviews, 13 students mentioned that they were mostly focused on the tablet as they were writing notes or drawing on the avatar there. Three participants preferred to look at the projection on body, and three participants split their time between the tablet and projection. The students commented that it was "*more important and easier*" to "*always*" focus on the tablet, because it helped them "*drawing annotations*". In that way, the tablet interface drew the students' attention away from the projection in the classroom, thus causing an attention split. While the students commented that they spent a large part of the class focusing on the tablet interface, they also found the projection provides "*good background (anatomical) knowledge*" and seeing the "*muscle projected on a real-life human body made it more realistic*".

6 STUDY 2: MOTION CAPTURE SYSTEM AND CUSTOM PEN INTERFACE

Study 2 Implementation

We made major improvements in accuracy, latency, and interaction with the *Augmented Body* system through re-designing it. Study 1 showed that the accuracy and latency with Kinect sensor is not good enough for projecting muscle activities during complex, fast movements. Tracking accuracy for AR systems are especially important in medical training and thus often affects usability [21]. We upgraded the skeleton tracking hardware by using a 12-camera OptiTrack motion capture system instead of the Kinect sensors (Figure 2(b)) and used retroreflective markers with Velcro stickers to put on the volunteer student's clothing (Figure 1(a)). This enabled sub-millimetre precision tracking of the volunteer's movements as well as improved latency in projection – enabling the volunteer to perform complex fast movements (e.g., kicking, bowling, etc.). We developed our own projection mapping system to work with this motion capture system.

We also designed a 3D printed physical *pen* with markers instead of the stylus in study 1 (Figure 3(a)), thus enabling the teacher and students to draw directly on the volunteer's body and to select muscle(s) or bone(s). We developed a projected palate (Figure 3(b)) which the teacher used to select brush size, color, eraser, create groups of muscles/bones, and to selectively turn on/off the muscle and skeleton view as well as remove specific muscles to reveal the inner layers (Figure 4(a)) using the developed pen. In this study, we excluded the tablet interface, we discuss the rationale later.

Study 2 Deployment as a Part of Curriculum and Evaluation of learning Outcome

We deployed the *Augmented Body* (AB) system as a part of the curriculum of the first year (semester 1) graduate physiotherapy students. There were 101 registered students in the practical course, who were randomly assigned into 4 groups (named G1-G4) of 24-26 people each. AB was deployed in the 11th and 14th week of the semester. The content was carefully designed and agreed upon by a group of teaching staffs to suit the regular standard of teaching content for the 11th week and advanced content for the 14th week deployment. This was to discern the impact of the developed technology on relatively easy and difficult content. Each class was 1 hour long (Figure 4(b)).

The students completed a mental rotation test (MRT) [24] (10 minutes) at the beginning of the study to measure their ability for visualizing rotation of complex structures. In the 11th week's class, group 1 and 3 participated in the projection-based (Pr) class while group 2 and 4 were taught the same content using traditional (Tr) teaching methods. This was reversed in the 14th week's class. In each class, the students completed a written examination (10 minutes) to evaluate their pre-existing understandings of the content (Pre-Test). Then the teacher lectured for about 30 minutes with the help of a volunteer student (with or without AB), who performed various body movements as instructed, similar to study 1. At the end of the lesson, the students attended the written examination again (same questions), so we could measure the learning outcome from the delivered lecture (Post-Test).

The pre-/post-test in study 2 was designed to see how the students could apply the materials covered in the session to a different movement scenario. For example, in week 2, the lecturing topic included various types of movements (isometric, concentric, or eccentric) of different muscles and the role of different legs in weight-shifting when a person climbs a staircase. The test questionnaire aimed to evaluate how the students use this knowledge to answer another scenario - "for a skier, the joint movement at the right and left hips and trunk when the knees turn to the right". While a physiotherapy teacher involved in this project designed the study protocol, it was then reviewed by independent academics at the Physiotherapy Department to ensure its suitability in evaluating students' learning outcome. The answer scripts were deidentified and were marked by an external independent examiner. 86 students completed both the classes and we included their data for statistical analysis. Afterwards, participants were requested to attend any of the three focus group discussions next week. A total of 41 participants attended these discussions.

Study 2 Data Collection

We collected (i) video recordings of all the teaching sessions, (ii) one MRT response from each student (iii) two written exam responses from each student in each teaching session, (iv) any paper notes students made during the teaching sessions, and (v) audio recordings of focus group discussions.

7 STUDY 2 FINDINGS: EVALUATING LEARNING OUTCOMES OF *AUGMENTED BODY* SYSTEM

The outcome of the usability analysis in study 1 highlighted the benefits of annotations through drawing on the model, yet the implementation of the tablet introduced many usability concerns that might have impacted the educational benefits of the system. The tablet played an important role for annotation, which is considered a primary task in the physiotherapy classes, essential to students' learning [11]. To ensure the fair evaluation of educational outcome, we implemented another mechanism for annotation (motion-tracked pen), to mitigate the usability issues caused by the tablet interface. We also improved the accuracy and latency of the system by replacing Kinect with OptiTrack motion capture system, designed the motion-tracked pen to enable direct annotation on the body, and designed a projected palette that the teacher could use to select various options (select, draw, erase, switch views, etc.). These improvements removed the variables of sensor error and usability issues caused by the tablet interface, allowing us to zone in our focus on educational benefits of the *Augmented Body* system.

Comparing Students' Performance between Projection based and Traditional Teaching Classes

We began our analysis with investigating if there is significant difference in normalized exam-score improvement (NEI) between students in projection (Pr) and traditional (Tr) condition. NEI was defined as ((Post-Test Score −Pre-Test Score) * 100) / Pre-Test Score. We performed descriptive statistical analysis on NEI for both conditions. There were few outliers ($n = 5$) that were more than 1.5 box-lengths from the edge of the box in a boxplot. Inspection of their values showed that these students scored very low in their pre-test, hence resulting in a large improvement, which we did not consider unusual. Excluding these data points from further analysis had no impact on the conclusion, hence they were kept.

We checked the difference among NEI scores to perform a within subject comparison across two conditions. The difference did not satisfy the normality condition (Shapiro-Wilk test, $p = 0.009$), hence we performed non-parametric between subject Wilcoxon Signed-rank test. This test showed a statistically significant median increase in NEI score (22.5%) when students used the projection condition (52.78%) compared to the traditional condition (37.5%), $Z = 2.666, p = .008$.

We undertook further analysis to investigate whether performance depended on scores on Mental Rotation Test (MRT), which assesses students' skills in 3D visualizations. The MRT was administered at the start of study 2. First, we divided each group of students (G1-G4) into two subgroups – students who scored lower than the median MRT score ($n = 42$) and the rest ($n = 44$). Lower MRT score indicates lower spatial cognitive ability or lower spatial visualization skill [24]. We checked the necessary pre-conditions for within subject comparison. For lower MRT students' group, we found that our data is not normally distributed (Shapiro-Wilk test, $p = .003$), hence we performed non-parametric Wilcoxon signed-rank test to compare the NEI values between these conditions (Pr vs. Tr). This test showed a statistically significant median increase in NEI score (29%) when subjects used the *projection* condition (50%) compared to the *traditional* condition (34.84%), $Z = 2.321$, $p = 0.02$. However, when we performed a similar analysis on the higher MRT student group, it showed a different result. We found the data normally distributed (Shapiro-Wilk test, $p = 0.776$) and there was no outlier, hence we performed a paired sampled T-Test. We found that the *projection* condition elicited a mean *NEI* increase of 16.06 (95% CI, -14.6 to 46.73, $d = 0.16$) compared to the *traditional* condition; however, their difference is *not* statistically significant, $t(43) = 1.06$, $p = 0.297$.

So, from these two hypotheses testing, we can see that the initial significance among *projection* and *traditional* conditions arose from the students who struggled to mentally rotate images in their MRT than the other group. It indicates that while most students showed better NEI scores in *projection* than in *traditional* condition, the difference is statistically significant only for students with lower MRT score. This is further supported in our qualitative data from focus group discussions, as discussed later.

We also compared NEI scores for all students in *projection* condition between week 11 (easy content) and week 14 (difficult content). We found that our data is not normally distributed, therefore we utilized a between subject Mann-Whitney U test (non-parametric equivalent of Two Sample T-test) to analyze the NEI scores between these two groups (G1, G3 vs. G2, G4 in our data). Mann-Whitney U test retains the null hypothesis that the distribution of NEI in both groups are same ($p = 0.279, U = 799, Z = -1.083$). A similar analysis for Tr condition between Week 11 and Week 14 data retains the null hypothesis too ($p = .297, U = 1044.5, Z = 1.043$).

This indicates that there is no clear evidence of using either *projection* or *traditional* teaching methods for different complexity of contents. This was further evident in our qualitative data where students had different opinions on how *Augmented Body* could help them at the beginning of the semester vs. towards the end of the semester.

Benefits of On-Body Projections

The students could readily see how the projection mapping based AR can help in their learning: "*It's life size, it's moving. I think both of those make it good and it's a real person!*" Visualizing the movements helped them by reducing their cognitive load during the lecture and made it easier to relate the description with the actual anatomy:

> "*When you're kicking this way [with projection] and teacher says, "what's happening at that hip?" Whereas if he just sat there and said, "what's happening to your right hip when you kick a ball with your right foot across your body [in traditional class]?" - Hearing him say that and then seeing like this, then you just look at the hip and - oh, it's like slightly internal rotated!*"

Students commented on how watching the muscles projected on the moving body bridged the "*huge disconnect*" between "*learning about movements in isolation and then putting it all together to actually functional movement*". Particularly, it helped them in understanding "*synergies in all those different actions happening at once*".

Students were unanimous that on-body projection helped them in both understanding teacher's question and responding to it: "*[It was] easy on the projected, because everything is already there so you can just point to it and like see where it is.*" Students discussed how the system could leverage the teacher's expertise and assisted them: "*When we go through a movement with [teacher's name], he is able to break it down in such a way that immediately I have a greater understanding of what's happening here [with/out projection]. But if we have something that involve the teacher's know how and a visual component to see – that is helpful for me.*"

There were different opinions on whether *Augmented Body* would be beneficial to use across different difficulty levels of subject content. Our statistical analysis, as presented earlier, was inconclusive. Some students expected it to be helpful in explaining "*big concepts*" at the beginning of the semester: "*It would be a really good way to introduce certain areas of the body to someone. This is really good for like teaching big concepts and introducing areas of the body to people who aren't learning about the tiny details*". Many of the other students disagreed: "*A full body movement would have been overwhelming at the beginning and it would've just been information overload*". Students recommended having various level of details or isolating just one part of the body in *Augmented Body* system during initial weeks and then to gradually progress towards more details: "*If this lesson is for talking about only leg muscles, so just isolating those, since you don't really need to look, like your arm, so that would just be more focused and clearer.*"

Changes from Traditional Teaching Methods

We initially expected that the students would often use the on-body drawing feature using the 3D printed *pen*. However, during the study and later discussions, it came out that they preferred to use the *pen* to select and highlight muscle(s)/bone(s) during the lectures, contrary to their regular practices during traditional classes. They found drawing useful only when the teacher tested their understanding of relationship between multiple anatomical functions: "*The drawing is probably more of a revision sort of testing tool. Like if it's on skeleton mode, then you can sort of think the origin and the insertion [of muscles], then it's probably good to test.*"

While not institutionalized yet, we found that students are using various technologies to assist in their learning, e.g., flash cards for remembering anatomical references, software that shows static images or descriptions, various augmented reality applications (Complete Anatomy, Human Anatomy Atlas, etc.), and videos from various YouTube channels. Some of these apps allow them to inspect 3D anatomical systems with good details and the videos show muscle activations during (pre-recorded) movements. While they find these technologies very useful, they often require these features with live movements: "*[In videos] We see stuff in one plane, so being able to, like walk around and see everything will be good*". Also, as the videos are pre-recorded, they cannot always find the appropriate movements they are looking for. Hence, they recommended a mechanism to record and rewatch the movements demonstrated in their classes (discussed later).

Augmented Body for Practicing and Revisioning

Students envisioned *Augmented Body* not only as a resource for classroom teaching, but also for practicing anatomy knowledge on their own and for revisioning. In typical physiotherapy practical classes, any sort of video recording is prohibited due to privacy concerns, as students often wear minimal clothing while they practice on each other. However, as the *Augmented Body* projects an anatomy model on clothing, such restrictions do not apply. Students were unanimous about rewatching the recorded movements for revisioning: "*We're not allowed to video image things. So, if there was some modulated way of having it recorded for later [watching]. Even when you are just doing a step, many things are going there at once. To be able to see it again will be great.*"

While not anatomically correct, students suggested having contraction and expansion of muscles to be exaggerated during the projection: "*I know that like in real life you don't necessarily see muscles contract, but for the sake of learning, it will be really great if you could see when a muscle is activated.*" Students also anticipated AB as a practicing tool. For example, they wanted to use it for testing their knowledge about origin of muscles and connection with bones: "*[for example, if the Augmented Body system asks] can you put where this muscle would be? We have to draw it [on skeleton] and then put the muscle back and see. Oh, you are correct! Or, you epically failed!*"

Students also could see benefits of the *Augmented Body* with further development of the software. One main recommendation was about projecting straight lines or plane to help them understand the relative angle between muscles and bones during moments: "*it's more just like an overall grid – to visualize joint angles and stuff like that, to see movements relative to other parts, by sort of imposing a grid*". Another student added: "*Especially for movements in arc, like something that involves going just out of the set planes is hard to grasp. You need to learn the straight planes first, but then to put it all together into a complex movement.*"

Anther recommendation came about automatic recognition of different types of muscle movement to assist both in learning and self-testing their understandings:

> "*if you're stepping up, say for example, three colors of muscles are highlighted - something that's working concentrically, eccentrically, and isometrically, as opposed to you having to guess which one it is. If there's different modes, like there's questionnaire mode, there's also like teaching mode and the teaching mode actually tells you what's happening at the right time. If you had the program that could teach you on its own.*"

Other students agreed that understanding different types of muscle movement are "*complicated*" and "*hard to visualize*", so *Augmented Body* can assist by highlighting these.

Limitations of Augmented Body

Students identify (and we acknowledge) various limitations of the *Augmented Body* system. First, they could not zoom in to see small intricate body parts with larger details in the projected model. This could be solved using an additional screen in classroom where they could focus on a particular segment of the model in greater details. Second, as projection condition required some level of darkness, it was inconvenient for taking notes and we adjusted the rolling blind to allow more light in the section of the room where students sat down. Another limitation arose from the projection mapping system, as we used two projectors facing each other, at an angle from $3m$ height. Hence, students could not see the front and the side view together, or projection from underneath the model. This can be solved by adding more projectors to the system. Finally, while using OptiTrack motion capture system significantly improved the quality of the system, it may be considered very expensive for widespread adoption. Students understood and acknowledged the limitations of *Augmented Body* in its developmental cycles and expected it to be fully integrated with the curriculum: "*It's [AB] good. I can see once it would start using, it would be better and better.*"

8 DISCUSSION

The *Augmented Body* system was designed to support students learning anatomy concepts in physiotherapy classes. Based on our earlier research [11], we hypothesized that on body augmented projection would benefit this learning. We extended this prior work significantly to include (1) a fully functional system with projection, tablet interface, and motion-tracked pen (2) A usability analysis to determine which interaction mechanism works best and why, and (3) A study to determine educational outcome that was part of the curriculum, to ensure an authentic learning environment and realistic evaluation within a pedagogical context.

The usability analysis (study 1) showed significant benefits in terms of cognitive load for the projection-only condition over traditional teaching. We added pen-on-tablet interactions to provide a familiar input mechanism to our augmented reality body projection system for annotation. The free-form drawing function on the tablet was inspired by on-body painting in existing physiotherapy learning and teaching practice [11, 16]. We expected that this design approach would have led to improvement in cognitive load, as Oviatt [18] suggested that student's cognitive load is proportional to their familiarity with the provided interface.

While the participants found the tablet useful for visualization and drawing annotation and believed it to have the potential to positively impact their learning, our results showed significant negative impact of high cognitive load from the tablet condition. Study 1 revealed practical limitations of the tablet interface, including size, weight, text entry issues, etc. In effect, the tablet partly fulfilled its design goal, at the cost of extra cognitive demands on the students, negatively impacting the usability of the system.

One major issue with the tablet that may have caused the usability impact is the challenge of annotating on animated moving virtual body. The freezing feature we implemented in anticipation of this challenge was used regularly by the students during the study. However, we observed that when the student annotated on the frozen model on their tablet, there was a disconnection between the movement of the student volunteer and the virtual model on the tablet. This broke the dynamism which we consider as a key benefit of the design of *Augmented Body*.

Annotation Behavior and Types

Traditional method of body painting as a teaching exercise in clinical anatomy aims to provide an inside-out *visualization of internal anatomy* [16]. Augmented projection mapping adds dynamism to on-body visualization of the virtual anatomy. In other word, the annotation behavior changes to drawing muscle attachment *on the body* in order to aid understanding of dynamic body movements. In our results, we observed complex annotation behavior where the students expressed the desire to use the 3D printed pen to draw in mid-air, such as a vertical virtual line extending from the body indicating the center of gravity. In this way the annotation could *extend from the body to the physical environment.* This observation provides implication for designing future augmented visualization system for clinical education.

The results from these studies also demonstrated additional types of augmented annotations that was not seen in a traditional classroom: *highlight* (study 2) and *mid-air annotations* (In both study 1 and 2). The design of the 3D printed pen was aimed at supporting direct manipulation for the teacher and students to draw annotations on the body. However, during the study, the pen was mostly used to highlight muscles or groups of muscles that were active during a demonstrated movement. This usage was also observed with the tablet interface where the participants colored in the muscles as a group to highlight its involvement in any particular movement.

Hybrid Interactive System

Incorporating the use of *Augmented Body* with the curriculum was challenging; however, it provided us with valuable insight on the learning outcome resulting from its usage, which may not be possible with voluntary involvement of student participants in a lab-based evaluation. Our analysis showed significant improvement in students' learning outcome resulting from the deployment of the *Augmented Body* system using 3D pen, while a negative usability impact on cognitive load using pen-based tablet interface.

Both of our implementations of *Augmented Body* in study 1 and study 2 are considered hybrid interactive systems, combining projection mapping visualization and pen-based interaction. In study 1, as the pen-based tablet interface was implemented on the tablet screen rather than on-body projection, there were two *separate mediums* in this study – projection and touch screen. Whereas in study 2, the system allowed pen input on the *same medium* of on-body projection. The issue of attention split as discussed in our findings (study 1) can be put down to the separation of the projection and touch screen mediums, which was not seen in study 2 when we enabled the same pen-based interaction on projection mapping. This provides useful insights into the approach of multimodal integration [22] for future AR based interactive systems.

Spatial Cognitive Skills

A closer inspection of the exam scores (study 2) revealed that the overall improvement is influenced by students' pre-existing spatial visualization capabilities. Students with lower spatial visualization skills may struggle to rotate images mentally. Rotation of complex muscles have been identified a major challenge in physiotherapy classes in existing research [11]. Hence students with weaker mental visualization capacity (reflected in their MRT score) had significantly greater increases in the learning scores when compared to student with higher visualization abilities. This result encourages new ways of thinking about technological interventions to support students who often struggle in traditional classroom settings.

Viewpoints and Visualization

While the on-body projection supported the learning of the students in the class, the experience of the student volunteer who acts as the body surrogate was unknown. During the development and testing, we discussed the usage of a mirror placed in front of the volunteer to allow them to see their own body. We extended this exploration in a public exhibition setting [12], and discovered that on-body projection enables a connection between the information and the target user of the projection. The effect of this finding in an educational setting is an intriguing premise for future studies.

9 CONCLUSION

We presented our journey across two studies to discuss the design, usability, and learning outcome evaluation of *Augmented Body* - a projection based augmented reality system developed for physiotherapy classrooms. Study 1 highlighted usability challenges for developing hybrid AR interactive technologies and the design considerations that influenced the usability of the system. We addressed these issues through refinement and conducted study 2 to evaluate learning outcome and experience. This study showed projection mapping can assist students in understanding complex rotational movements that they find difficult otherwise. These studies showed changes in students' note taking behavior and how the interactional activities shifted from drawing to highlighting, as provided by technological affordances. We showed how these systems caused significant improvement in students with lower mental visualization capabilities compared to others and demonstrated the potential for educational AR technologies to enhance learning experience in classroom settings.

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