The Human Muscular Arm Avatar as an Interactive Visualization Tool in Learning Anatomy: Medical Students' Perspectives

Yusuf Ozgur Cakmak, Ben Kei Daniel, Niels Hammer, Onur Yilmaz, Erdem Can Irmak, and Prashanna Khwaounjoo

***Abstract*—The perception of body ownership creates a sense of embodiment, which can be a powerful learning tool. Embodied learning can occur by watching an individual's body movement and also via human–computer interactions, such as virtual reality (VR) and augmented reality (AR). In this article, we designed and implemented a novel virtual body-ownership AR/VR tool for human anatomy—the human muscular arm avatar (HMAA). HMAA utilizes embodiment-based body ownership to explore the human hand/forearm musculature. The HMAA was trialed with medical students to explore the extent to which it could be used to aid student learning. The key findings of the usability study suggest that 98% ($N = 100$) of students found the tool extremely useful; 83% reported that the tool allowed them to engage with the learning materials, peers, and content effectively. Also, 10% of students mentioned that the HMAA fostered an embodied learning experience. This triggered an intentional exploration of instances suggesting embodiment in the data. HMAA is believed to have allowed individuals to visualize and conceptualize abstract ideas that would have been otherwise challenging using static models. The outcomes of this article indicate the significant potential of body-ownership-based self-learning tools for anatomy. However, further studies using learning outcomes are needed to investigate the potential advantages of body-ownership-based tools compared to current learning techniques.**

***Index Terms*—Anatomy learning, augmented reality (AR), data visualization and learning, digital learning tools, embodied cognition, embodied learning, usability study, virtual reality (VR).**

I. Introduction

THE body-ownership sensation that contributes to embodiment-based cognitive processes is a complex phenomenon. Body ownership can be described as the feeling that our body belongs to us and that it is distinct from other people's bodies [1], [2]. Also, it is the perceptual distinction between one's own body and the environment, deemed necessary to establish a baseline for higher cognitive functions and self-awareness [3], [4]. Further, body ownership is used to refer to the sense that one's own body provides sensations [5], [6].

Cognition, on the other hand, is an essential aspect of human learning, which is critically based on physical actions that produce simulations of previous sensory-motor experiences [7], [8]. Moreover, the reactivations of acquired sensory-motor memory traces are essential for memory performance. For instance, research suggests that people are likely to remember a list of action verbs better when they perform the corresponding actions via embodied cognition in the learning phase, compared to when they merely read the words [8]–[10]. By performing actions, the memory not only improves but significantly contributes to enhancement in reading [11], [12]. The direct sensory-motor experience during learning and embodied cognition, therefore, has remarkable benefits and contributes to subsequent recall. Over the last 20 years, work surrounding theories of embodied learning demonstrated the role of the putative mirror neuron system (MNS) in humans [13]–[17]. It is also shown that these phenomena (in which the embodied learning and mirror neurons engage) are not limited to human-to-human interaction but also human–robot interaction [18], [19] as in the case of prosthetic limbs.

The fundamental principle of embodied learning is grounded on the belief that when people use their bodies to learn, they are actively engaged in the process than reception in information through teaching, reading, and other forms of static interactions of teaching/learning tools [11], [12], [20], [21]. The embodied learning approach attributes learning to the inseparable link between brain, body, and the world. It suggests that the active human body can alter the function of the brain and, therefore, the cognitive process toward better understanding and, ultimately, enriched learning experiences [22]. Recently, there has been a growing trend to embrace embodied learning as an instructional method that enables students to build meaningful connections between physical activity and the critical principles and relationships in domains such as math and science [23].

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Furthermore, new technologies are being developed that use natural human physicality and gesture as inputs [23]. These technologies include computer-assisted learning [24], mobile learning, virtual reality (VR), augmented reality (AR), and motion-sensing technology [25]. In particular, VR/AR is becoming more prominent. AR itself can be described as a combination of the virtual and real environments [26], whereas VR replaces your vision. VR/AR is one of the potential approaches needed to fulfill the gap in traditional anatomy education because it enables users to experience learning real time via interaction with real or virtual objects in the three-dimensional (3-D) space. Available applications, however, are more likely to be static and users' interactions are limited to a rotation of models or via clicking on active virtual buttons or reshaping the model [27]. Such interactivity implementations can potentially be improved by embedding dynamic and interactive virtual body-ownership-based approaches, with an avatar such as the option to foster self-directed learning applications. Virtual embodiment is one of the approaches used in building VR/AR games where users interact via avatars. The use of dynamic and interactive avatars or, in other words, embodiment, however, is limited in VR- and AR-based teaching/self-directed learning tools in the domain of human anatomy.

To this end, in this article, we present a virtual embodied self-learning environment for learning human anatomy in one of the most complex parts of the human body: the hand musculature and function. Considering the potential benefit of a virtual embodiment for self-directed learning with 3-D visualization, we developed a dynamic working human forearm and hand muscles avatar system. As an initial investigation into this system, usability and user evaluation were undertaken to examine how medical students experience the tool and to the extent to which it fostered students' engagement and potential understanding of human hand/forearm musculature.

II. Methods

A. Development

1) Development of a Dynamic and Interactive Virtual Body-Ownership-Based Self-Learning Tool, The Human Muscular Arm Avatar (HMAA): An interactive and dynamic virtual avatar for hand and forearm muscles was developed using Unity software and Leap motion camera. The anatomical hand/forearm muscles model was purchased from a portal (Turbosquid) of commercially available 3-D models. An infrared camera (Leap Motion) was used to detect the hand movements. The avatar software that determines the finger, hand, and forearm movements was coded with the aid of Unity software under the supervision of an experienced anatomist. The muscle function definitions were based on Gray's Anatomy [28].

The Leap Motion controller is a portable tracking device that detects movements, gestures, and discrete positions of the hands and fingers. It also provides the ability for gesture-based human–computer interaction applications. With its innovative gesture and position tracking system, it can capture real-time hand and fingertip motion and position with a submillimeter (0.01 mm) accuracy. Leap Motion uses three separate infrared emitters and two monochromatic IR cameras to capture the raw data motion of the hand without using motion capture markers [29].

The working principles of the Leap Motion [30] can be described with these steps.

1) The controller captures the raw sensor image data using its emitters and IR (infrared) cameras.
2) Raw data are written into the controller's memory, and resolution adjustment is performed.
3) Raw Image data are streamed to the computer.
4) The hand image is extracted and segmented on the computer.
5) Data are analyzed, and the final virtual hand data are extracted from these processed images.

2) Software Development: The virtual embodiment based HMAA is a finger/hand/forearm motion analysis tool that tracks the motion of the finger/hand/forearm via the Leap Motion controller and detects which muscles are active in real time. In essence, the system is used to connect the real body movement with the 3-D virtual body part (hand and forearm) displayed on a 2-D screen. It was developed for Windows and macOS and implemented using the Unity3D engine. The Leap Motion controller and mouse can control the application. Camera zoom-in zoom-out, the camera rotation, and the mouse controls compose the other user interface interactions.

The analysis process of HMAA consists of five steps. The details of these steps are described as follows.

1) *Capturing motion data*: The Leap Motion controller captures the data of the finger/hand/forearm motion. These data contain scalar hand/finger/forearm features, 3-D vector positions, and quaternion rotations.
2) *Processing scalar finger/hand/forearm data:* The scalar data are processed according to base values. For example, the minimum distance between two fingertips is taken and normalized to the other distance values regarding their base distances.
3) *Processing vector finger/hand/forearm data:* The vector data, according to their base values, are processed using relative positions of the fingers and are calculated by subtracting finger positions from 3-D shape origin.
4) *Creating the finger/hand/forearm features:* All processed data are collected and calculated for the motion of the finger/hand/forearm.
5) *Processing the result of the hand motion:* The data of finger/hand/forearm motion are processed for selection for the active muscle.

To easily categorize the active muscles, the hand joint data are processed in different ways. First, the angles between different bones in the fingers are defined in the x, y, z dimensions. An arbitrary dimension defines certain angles that cannot merely be defined in x, y, z dimensions, and consequently, quaternion values are used for these joints. Finally, to calculate angles of wrist movement, wrist angles are defined by yaw, pitch, and roll axes of the ankle.

The HMAA is based on real-time hand gestures to classify hand motions and their states. For this reason, two different gesture categories are created in the application: static gestures and dynamic gestures. The static gestures determine the

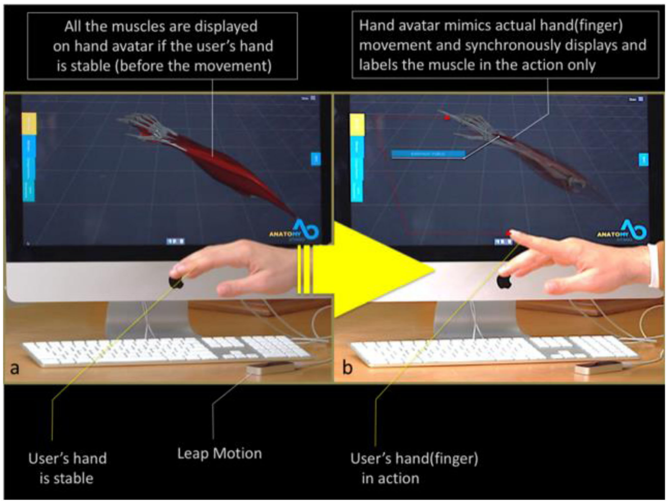

Fig. 1. (a) Photo before the action of the index finger (model displays all the muscles on the forearm and the hand). (b) Picture after the index finger action (extension) where the system dynamically mimics the index finger movement and displays and labels the appropriate muscle for that particular action (extensor indices). (Appendix A video shows the system in action.)

hand position when the hand is not in motion. These gestures are based on the position of hand, wrist, and fingertips. While the dynamic gestures are used when the position of the hand changes at a particular time interval, the dynamic gestures can be described using vector and quaternion values, and these gestures determine the majority of the muscle states.

In this innovative tool, when a user moves a finger, hand, or forearm, the infrared camera detects the movement, and the software interprets the data and displays the actual position of the finger, hand, and forearm about the skeleton. Also, the system highlights and labels the muscle(s), which is related to the user's movement (see Fig. 1 and movie in Appendix A). Another advantage of this application is the ability to detect the elegant movements of the fingers and hand without the need for any motion tracker gloves, suit, or accelerometer.

B. Usability Study

To investigate students' perspectives on the HMAA as a learning tool, usability testing was undertaken with volunteer third-year medical school students ($N = 100$). The University of Otago Human Ethics Committee approved the project (reference code 16/026). The usability study focused on how medical students experience the software when exposed to basic concepts in muscular anatomy.

Participation was voluntary, and those who took part in the study were at the time learning the functional anatomy of the hand musculature. The class was split into groups, and within each group, each student was asked to use the muscular arm avatar for 15 min in an open-ended manner under the supervision of the responsible researcher.

After the 15-min trial with the HMAA, an online questionnaire was then given to the students (see Appendix B). The questionnaire comprised of 14 items consisting of closed-ended and open-ended questions. The use of a questionnaire is not uncommon in carrying out usability and user experience studies [31].

TABLE I
DEMOGRAPHIC INFORMATION OF THE PARTICIPANTS

Variable	n (%)
Gender	
Male	42(42)
Female	58(58)
Is your first language English?	
Yes	87(87)
No	13(13)
Ethnicity	
New Zealand European	62(62)
New Zealand Maori	9(9)
International student	8(8)
New Zealand Indian	7(7)
Two or more races	6(6)
Samoan	3(3)
New Zealand Chinese	2(2)
Tongan	2(2)
New Zealand Caribbean	1(1)

The open-ended questions generated qualitative responses, which were used to explain responses to the quantitative questions. The first part of the questionnaire (Appendix B) consisted of questions on student demographic information, while the second part posed questions about student experience with a virtual embodied self-learning tool. The main research questions guiding the study consisted of the following.

1) How useful was the HMAA as a learning tool?
2) How did the students engage with HMAA?
3) To what extent could the use of HMAA support student learning of muscular anatomy?

1) Participants: There was almost an equal distribution of males (42) and females (58) in the sample. The majority of respondents identified English as their first language, and over half of them self-identified as a New Zealander of European descent, and only 9% identified as Maori. Table I presents the respondents' demographic information. The demographic distribution reflected the population of the class.

2) Data Analysis: The questionnaire generated quantitative and qualitative data, which were analyzed concurrently. There were eight closed-ended questions measured on a Likert scale. The quantitative data were analyzed using SPSS 22 from IBM, with descriptive statistics used to summarize the results.

Moreover, responses to open-ended questions were compiled and thematically analyzed using NVivo from QSR International. The process of conducting qualitative data analysis involved reading and re-reading the open-ended responses [32]. Themes were identified within segments of texts associated with the closed-ended questions and were coded for prevalence as well as the frequency of occurrences. Selected quotations were used to illustrate particular themes.

III. Results

A. How Useful was the HMAA in Learning Anatomy?

Over half of the respondents said that they found the HMAA extremely useful as a learning tool (62%) (see Fig. 2).

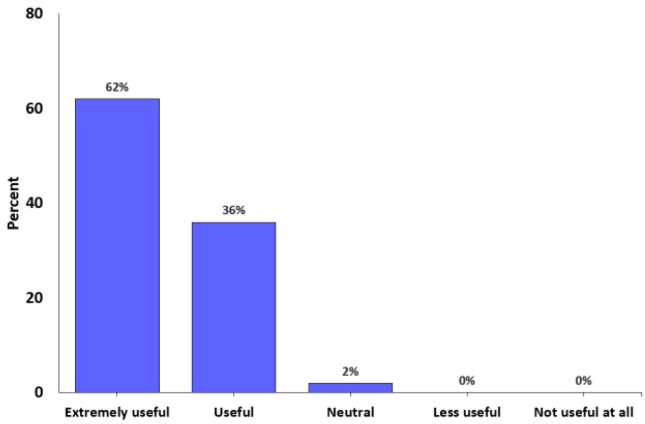

Fig. 2. Results for the usefulness survey of HMAA as a learning tool for anatomy.

Students found the tool useful to their learning. They stated that using the application enabled them to move away from rote memorization to active learning and application. However, no significant differences relating to the usefulness were found when separating the student cohort based on sex and ethnicity (see Table I). A selected statement from a participant regarding the value of the software is provided as follows:

> *"Learning the muscular system often involves memorizing details about each muscle, such as where a muscle attaches to bones and how a muscle helps to move a joint. In textbooks and lectures, these details about muscles are described using specifically limited vocabulary that is hard to understand and imagine. However, this project makes it all much more comfortable as you see your forearm and the muscles inside on the screen simultaneously."*

The sample consisted of students whose first language is English and others with a different first language. To garner more insight into the ease of language used in the interface, Spearman's rho correlation coefficient was computed, aiming to assess the relationship between participants' first language and the usefulness of HMAA. A strong positive correlation was identified between students' language background and the perception of the usefulness of HMAA in learning anatomy ($r = 0.74$, $p = 0.033$). The results suggest that the language used in the presentation of the interface and the content of the tool were simple to understand. No further significant correlations were observed.

1) Embodiment and Learning: Based on the concept of embodied cognition and body ownership sensation, students were able to relate the experience they gained from using HMAA avatar to their hand. The ability to see one's arm movements in the virtual space was found to be a useful way of learning anatomy. One student described it as follows.

> *"In using a program like this, it makes it easier to visualize the anatomy on yourself. I am somebody who finds concepts easier to remember if they are portrayed in a way that I can relate to a real-life example, and I feel that this software allows this."*

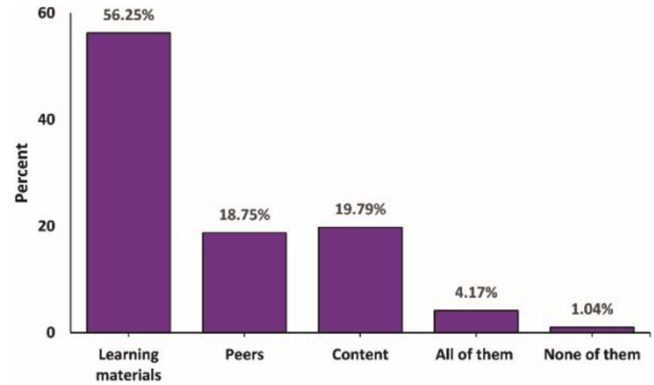

Fig. 3. How HMAA helped in actively engaging students in the learning process.

Looking at their own virtual hand and feeling a sense of body ownership, anatomy students indicated that HMAA could make learning better as they could easily relate abstract concepts to reality as summarized by a student.

> *"It lets me look at my anatomy and combine them with reference materials so I can look at my movements instead of a static image in a textbook."*

Respondents also mentioned that the application enabled them to visualize different parts/muscles of the arm that were highlighted by the program when moving their hand, and thereby enhanced their knowledge of these muscles. Others said this form of virtual embodiment was useful.

> *"It was beneficial to see which muscles are active and producing different movements."*

B. How Did Students Engage With HMAA?

Data suggest that respondents used the HMAA to support engagement with content (56%), peers (19%), and 25% indicated that the HMAA helped them to engage more with all aspects of the class (see Fig. 3).

> *"Peers, learning material, content, and lectures it has huge potential."*

Content in this context refers to the specific prescribed content of the course, and learning materials are all resources students were using when learning the subject matter. It should also be noted that while students used the HMAA system individually, they were able to interact with their peers while doing so.

Respondents also reported that the use of the HMAA facilitated a better understanding of more complex concepts, much better than a book.

> *"Great visualizing 3D rather than a 2D textbook, and it was useful to see the muscles in 3D and how they work and interact in different movements."*

Findings also suggest that the HMAA helped students to engage more with different aspects of the class, and in particular with the learning materials.

> *"It is engaging and accurate. It allows the user to see the muscular movements. It was good because you could get the 3D orientation."*

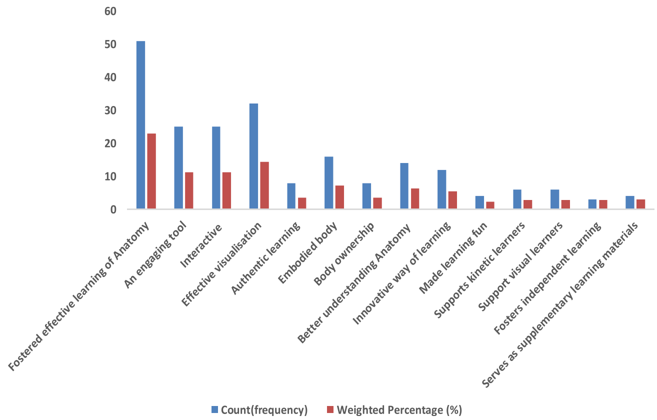

Fig. 4. Frequency and weighted frequencies of critical terms extracted from the responses to: how useful was the HMAA in learning anatomy?

Respondents also said the avatar also encouraged active learning, since they were able to engage in the manipulation of various aspects of the muscular arm and observed their movements.

> *"It encourages active learning because of the ability to visually see what muscles are working in what movements are largely useful."*

C. *Transformative Pedagogy and Enhanced Student Learning (To What Extent Does the Use of HMAA Support Student Learning of Muscular Anatomy?)*

Digital technologies provide enormous opportunities that can transform pedagogy in many ways. However, it requires faculty and students to work together in exploring and experimenting with technologies and learning spaces [33]. HMAA has the potential to transform the way anatomy is taught and enhance the student learning experience. Instead of over-reliance on presenting learning materials using static models, HMAA can be utilized to support multidimensional visualization of learning materials [34]. The results of the usability testing suggest the AR aspect of the software may be able to enhance students' learning experiences in the future (see Fig. 4). More specifically, it enabled them to quickly visualize and conceptualize abstract ideas that would have been otherwise challenging using static models. One respondent also pointed out that the ability to see the movement of muscles helped them to integrate theory into practice.

> *"It helps in showing a real-world application of what we are learning as well as help learn content as you can see, manipulate it in front of you."*

Visualization techniques can support various learning activities. Students can use visualization techniques to identify and understand educational resources [35]. On the other hand, teachers can use visualization to understand student navigational pathways during their learning trajectories. Further, visualization can likely amplify cognition. Students predominantly declared that the use of the HMAA tool enhanced their understanding of anatomy and visualizing the movement of the human arm muscles, which was reported to have significant roles in integrating contact to practice [36].

1) Supporting Better Engagement in Learning Anatomy: Some respondents indicated that the visualization aspects of the software helped them better understand essential concepts in anatomy.

> *"This is a fantastic teaching tool to aid the understanding of anatomy."*

Others mentioned that anatomy is best learned using HMAA because the tool provides a better explanation of the function of the human body.

> *"More versatile than just looking in a book can appreciate the 3D nature of the anatomy nerve."*

Respondents also mentioned that the software is useful and suitable for a demonstration of the concept of muscles. It also helped others who would typically learn better through visualization, as one respondent indicated.

> *"I am someone who takes time to study because it takes a while to picture what I am interested in; this is very useful for me as it enables me to identify what I am looking for visibly. Therefore, making it easier to visualize vividly."*

HMAA was found valuable when presenting and visualizing details of the structures of the arm that would typically usually only be viewed physically. The interactive features of the software provided various options for learning muscles individually or all together. Moreover, it helped in understanding the movement of the muscles in the arm. Using their bodies, students reported that the software enabled them to observe the movement of their muscles, thus enabling them to appreciate their functions.

> *"It gave me a great opportunity to understand the forearm and hand muscles coordination of the movement and the relations between joint movements and forearm muscles."*

> *"It provides a more realistic way for us to visualize muscles. We can learn about them in 3D' in action rather than just memorizing the wrist and what they should look like what they do."*

Others said that using the tool was a fun way of learning anatomy and a way of integrating various concepts in the course.

> *"Because it shows exactly what you need to see to understand the muscles. A fun experience regarding learning."*

Respondents also mentioned that the software could potentially support self-directed learning. It enables them to take the initiative in their learning and explored learning through engaging with supplementary learning materials.

> *"Students can use them independently or as part of an in-class lesson, and teachers can use them to supplement or replace a traditional textbook."*

Further, frequencies of the key terms were extracted from a word cloud analysis using an information retrieval technique. The following formula was used to compute term frequencies and weighted frequencies: for a term i in document j: ($W_{i,j} = tf_{i,j}$$*LogNdf_i W_{i,j} = tf_{i,j}$$*$Log/$Ndf_i$), where W is the weight, $tf_{i,j} =$

total number of occurrences of term i in a document j; $\mathrm{d}f_i$ = number of documents containing i. Moreover, N = the total number of documents with terms of interest [37]. Terms that did not make sense were removed, and a final list of words together with associated phrases are presented in Fig. 4 and in Table II. These outputs suggest that the software facilitated ease of visualization of the movements of muscles, and thereby contributed to understanding. Using the tool fostered a clear understanding of the content. Students mainly found the ability to visualize the movement of their muscles useful in relating abstract concepts to more detailed knowledge. Overall, the hand avatar contributed to better student understanding.

IV. Discussion

Numerous methodologies of teaching and learning have evolved with time, and recently, educational tools that use human–computer interaction for self-learning applications are becoming more prominent. In particular, VR- and AR-based 3-D models and visualization systems are being utilized to support human anatomy education. With this in mind, we created and investigated the HMAA system, a novel embodiment-based VR/AR body-ownership learning tool for human arm musculature. Usability tests and investigation results indicate that our application significantly enriched perceived student learning and highlight the positive impact of embedding virtual body ownership into anatomy educational technologies.

Students' self-reported that the body-ownership approach helped them to visualize the movement of muscles in the arm as their own and enabled them to quickly integrate anatomical knowledge, as well as understand muscle function. We believe the HMAA fostered a human–computer interaction similar to the human–human interaction, which makes use of body movements [25], [38] and the MNS [13]–[19] for embodied learning. This article substantiates the view that embodied learning constitutes a form of pedagogical theory that emphasizes the use of the body and body ownership in educational practice as well as student interaction in digital environments [39]. In particular, for this article, as HMAA allows visualization of working muscle groups, it also may enable students to obtain a better understanding of muscle recruitment during specific movements, which is often tested in the medical curriculum.

Embodied learning approaches enable learners to experience learning through play, experimentation acting, feeling, thinking, and being-in-the-world, rather than as separate physical and mental qualities which bear no relation to each other [40]. Students in our study reported that using the hand avatar platform in learning anatomy was enjoyable and mentioned that using the software helped them to understand complex concepts and enabled them to retain knowledge. They also stated that activities through augmented technology, which afforded them an embodied body ownership experience, as demonstrated in the hand avatar application, helped them to gain a better understanding of abstract concepts and incorporate potential learning activities into their learning materials.

Results in this article revealed that actively engaging with the hand avatar application provided students with an excellent opportunity to understand the forearm and hand muscles coordination and movement, as well as the relationships between joint movements and forearm muscles. Furthermore, respondents reported that the use of the HMAA application provided a more realistic way for them to visualize the movement of the muscles in their body rather than memorizing information. However, although desirable, we did not verify students' self-reported learning experiences with alternative evidence (e.g., learning scores or final grades in the course). We acknowledge that the outcome of this research is exploratory, and the extent to which students perceived enhanced learning contributes to tangible learning outcomes, should be investigated with future research. Also, the dynamic and interactive embodied approaches of teaching/self-learning applications need to be compared with other methods to clarify the significant difference in the learning and memory outcomes. Nonetheless, a logical presumption is that the HMAA allowed individuals to visualize and conceptualize abstract ideas that would have been otherwise challenging using static models. The degree to which this is accurate can be tested in future studies.

V. Conclusion

In conclusion, to the best of our knowledge, we implemented and tested the HMAA, dynamic and interactive embodied human anatomy self-learning tool for the first time in literature, to teach a complicated part of human muscular anatomy: the human hand and forearm. The student feedback underlined the usefulness and positive aspects of engagement with HMAA. The outcomes of the present study indicate a potentially powerful effect of dynamic and interactive embodiment implementation into human–computer-based self-learning tools for the human body.

VI. Limitations

This article has provided us with rich insights into the value of HMAA in promoting the student learning experience. However, the research carried out was exploratory, with qualitative type questions constituting open-ended responses from students. In future, more objective measures such as written anatomical tests that query students on the functional muscle connections/locations will be used to further measure particular learning outcomes associated with the use of HMAA. Furthermore, the use of the embodiment reported in the study is limited, evidence of which was extracted from the student's self-reported responses to the open-ended questions. Our next study will involve designing experiments to test particular aspects in which HMAA enhances embodiment, with comparisons with passive 3D visual computer models and the extent to which it fosters concrete learning outcomes.

Appendix A
Video of HMAA in Action

Link for the Hand/Arm avatar in action video.[1]

[1] [Online]. Available: https://www.dropbox.com/s/50dmq2puibsusah/Avatar%20%281%29.mp4?dl=0

APPENDIX B
USABILITY STUDY QUESTIONNAIRE OF HMAA

Interactive Muscular Avatar of the Hand and Forearm: This project will investigate the latest affordances of augmented reality technologies and their effectiveness in supporting student learning of human muscular system of the hand and arm. The project will involve the development of a tool that incorporates software to help with interpretation of the data, displaying the actual position of the hand and arm with human skeleton. Further, the tool will support students in highlighting and labelling the movement of hand muscles. Medical students from Otago will be the target users of the tool. We are requesting about 10 minutes of your time to provide us feedback regarding the usability of the tool and its contribution to your learning.

TABLE II

1. Are you a student in Otago University?
   - ☐ Yes
2. How do you identify yourself?
   - [▾]
3. What is your gender?
   - ○ Male
   - ○ Female
   - ○ Other: [ ]
4. Is your first language English?
   - ○ Yes
   - ○ No
   - ○ Other: [ ]
5. Have you used Augmented Reality before?
   - ○ Yes
   - ○ No
6. How useful was the HMHA in learning Anatomy?
   - ○ Extremely useful
   - ○ Useful
   - ○ Neutral
   - ○ Less useful
   - ○ Not useful at all

   Briefly provide the reasons for your choice.
7. The HMHA helped in engaged more with
   - ○ Peers
   - ○ Learning materials
   - ○ Lecturers
   - ○ Content
   - ○ Other: [ ]

   Briefly provide the reasons for your choice.
8. Overall the availability of HMHA has contributed to my learning
   - ○ Strongly agree
   - ○ Agree
   - ○ Neutral
   - ○ Disagree
   - ○ Strongly disagree

   Briefly provide the reasons for your choice.
9. Did you encounter any problem using the HMHA tool?
10. Was there anything in the HMHA tool that you missed but was expecting to see?
11. What were the three main things you liked about using the HMHA tool?
12. What were the three main challenges (if any) you encountered using HMHA tool?
13. Would you recommend your peers to use the HMHA tool… briefly explain.
14. Briefly tell us how the use of the HMHA tool contributed to your learning

APPENDIX C
THEMATIC ANALYSIS

TABLE III
A GENERAL INDUCTIVE ANALYSIS OF THE QUALITATIVE DATA: HOW USEFUL WAS THE AUGMENTED REALITY IN LEARNING ANATOMY?

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Theme	Verbatim Example of Quotations	Interpretation of the Themes
Learning fun	• It was fun. It means you can actually link a useful and physical stimulus for learning, i.e., I can flex my wrist and see what happens under the skin [Respondent 1] • Learning anatomy without boring books with such an entertaining device is quite useful and you do not realise how much time you spent on learning this useful and futuristic way of learning [Respondent 2] • Because it shows exactly what you need to see in order to understand the muscles • More of a detailed whilst a fun experience in terms of learning [Respondent 3]	Students reported that using the software for learning Anatomy was more engaging and fun.
Effective visualization	• The ability to visually see what muscles are working in what movements is largely useful [Respondent 1] • Easily able to visualize/conceptualise the muscles involved with movement [Respondent 2] • Made it very easy to see the function of each muscles [Respondent 3] • Good to see which muscles are in action as makes it easier to remember [Respondent 4] • Very easy to visualise the muscles causing the movements. Great to be able to individually select muscles that are highlighted when active [Respondent 5] • Really cool to see which muscles do what or you do the movements. Very memorable [Respondent 6] • Useful to see the muscles in 3D and how they work and interact in different movements [Respondent 7] • New perspective Easy to visualize • Visual way of integrating anatomical knowledge with movements [Respondent 8] • Fantastic, interactive visualization! I love this [Respondent 9] • Seeing information in motion means I can engage with it and see active changes as they occur [Respondent 10] • In using a programme like this, it makes it easier to visualise the anatomy on yourself [Respondent 11] • Makes learning visibly applicable and easier to remember [Respondent 12] • Very visual - good learning tool very applicable [Respondent 13] • Amazing way to visualize interact with anatomy • It is amazing to watch Very relatable to read life! [Respondent 14] • I like how you can visualize the muscles - so useful for learning and for patient education [Respondent 15] • It was really good because you could get the 3D orientation [Respondent 16]	The ability to visualise abstract concepts was viewed as an effective way of learning. The visualisation also made it easier to see the structure and functions of muscles in the human hand.
Fosters independent or supplementary learning	• Students can use them independently or as part of an in-class lesson, and teachers can use them to supplement or replace a traditional textbook. It would be more beneficial for both students and lecturers than any other traditional method of learning anatomy [Respondent 1]	Students said the software had the potential to support self-directed learning and could also be used as a supplementary learning resource.
Authentic learning	• It helped with a real-world application of what we are learning as well as help learn content as you can see, manipulate it in front of you [Respondent 1] • Great to see all the active muscles night in front of my eyes [Respondent 2] • Good real like a demonstration of muscles novel concept [Respondent 3] • Great to see how the muscles function together but also very fast so you can't see which muscles were involved [Respondent 4] • Helps apply learning and knowledge to reality [Respondent 6] • It provides a more realistic way for us to visualise muscles. We can learn about them in 3D' in action rather than just memorising wrist they should look like what they do [Respondent 7] • Excellent to be able to translate muscle movement into actual real life movement [Respondent 8]	The software made it easier to gain knowledge of abstract concepts and relate to real-world functioning of the hand and arm.
Body ownership and embodied learning	• In using a programme like this it makes it easier to visualise the anatomy on yourself [Respondent 1] • I am somebody who finds concepts easier to remember if they are portrayed in a way that I can relate back to a real life example and I feel that this software allows this [Respondent 2] • Able to relate my own movement to active muscle [Respondent 3] • It lets me look at my own anatomy and combine it with reference materials so I can look at movements instead of a static image in a textbook [Respondent 4] • It was amazing to see the muscles on yourself [Respondent 5] • You can see the individual muscles in your hand, and in a 3D view as well [Respondent 6] • Nice having visual demonstration in 3D cool to see the anatomy we learnt from lectures and textbook in “live action” [Respondent 7]	Because students were using their own hand to learn the anatomy of the hand and arm, they were able to relate the knowledge and thereby learn better what would have otherwise been complex.
Fosters better understanding	• Anatomy is best learnt in 3D - AR allows better understanding of the function [Respondent 1] • Can see in a real time. Practical way what you are trying to learn [Respondent 2] • It enables you to associate the movements you are doing with the muscles displayed on screen in real time, as you are moving them. It provides a visual aid to the learning process [Respondent 3] • I am somebody who finds concepts easier to remember if they are portrayed in a way that I can relate back to a real life example and I feel that this software allows this [Respondent 4] • Gives an idea of when different muscles are being activated for a given movement, which is invaluable [Respondent 5]	Using the software provided a better understanding of the functions and structure of muscles.

TABLE III
Continued

	• Interesting seeing muscles in 3D and what are used in normal movements [Respondent 6] • Helped that how many muscles were involved in a movement [Respondent 7] • It would be very useful in learning movements of muscles [Respondent 8] • Good to see muscle actions in real time [Respondent 9] • Had to do slow movement to correctly pick up muscles used and display them for long enough to see [Respondent 10] • Helps relate structures to movements, helps to understand muscle function [Respondent 11] • Showed movements would be helpful to have other info e.g. arteries and nerves [Respondent 12] • The immediacy of information and action Having muscles highlight on activation was very interesting [Respondent 13] • Can see where the muscles and when actions they perform [Respondent 14] • Really cool to see the real life appreciation of the muscle movements. Would be excellent learning tool if had more time [Respondent 15] • Nice to see the muscles in action. Cool to be able to visualise muscles on yourself as you move them [Respondent 16] • It was interesting seeing stripped back anatomy and muscle involvement first hand while using the arm. • Extremely useful to see which muscles are active and producing different movements. Great visualizing 3D rather than 2D textbook [Respondent 17] • Very clear good image showing how the muscles function. Nice to connect the muscles with their associated movements [Respondent 18] • Can see where the muscles and when actions they perform [Respondent 19] • Really cool to see the real life appreciation of the muscle movements. Would be excellent learning tool if had more time [Respondent 20] • Nice to see the muscles in action • Cool to be able to visualise muscles on yourself as you move them [Respondent 21] • It was interesting seeing stripped back anatomy and muscle involvement first hand while using the arm [Respondent 22] • Extremely useful to see which muscles are active and producing different movements [Respondent 23] • It would be a very visual too to match muscle with function [Respondent 24] • Can see muscles clearly good to relate movements to active muscles [Respondent 25]	
Interactive and engaging learning	• An interactive and different way of learning anatomy lots of different options for learning muscles individually or altogether [Respondent 1] • It is engaging and accurate. It allows the user to see the muscular consequences of movements [Respondent 2] • It is much more interesting to see it in an interactive way rather than from a textbook. Gives a better representation of the 3D nature. Being able to see labelled muscles moving while I am moving them [Respondent 3]	The ability to manipulate the hand and fingers made learning interactive, engaging and relevant.
Support visual and kinetic learners	• The model allows fantastic visualisation and detail of structures that would usually only typically be able to be view physically, in a very realistic manner [Respondent 1] • I am a visual learner so this is very helpful. It captured my attention and was very interesting [Respondent 2] • It helps give a sense of reality to learning if you can see the muscles move as you move them. I imagine it would be very helpful for those students who are visual learners [Respondent 3] • I am a very visual learner. This combines visual input with practical activity [Respondent 4] • I'm someone who takes time to study because it takes a while to picture what I'm interested in, this is very useful for its enable to show what I'm looking for visibly [Respondent 5] • Can see muscles easily, it also a good tool for kinetic [sic] learners [Respondent 6]	The software was viewed much more relevant to students who identify as visual or kinesthetic learners.
Innovative way of learning anatomy	• At the moment it's useful because it provides a unique mainframe for learning anatomy which can be alternated and viewed from multiple angles [Respondent 1] • It's quirky in the sense that you are looking at your very own anatomy, which people will universally enjoy. When will you ever get this opportunity? [Respondent 2] • The technology itself is limited to the arm here, but it effectively highlights the potential of this technology as both a learning tool and for diagnostics [Respondent 2] • It's often difficult to visualise the three dimensional movements of muscles at a joint - this made picturing these movements and the muscles involved much easier! [Respondent 3] • More versatile than just looking in a book, can appreciate the 3D nature of anatomy nerve [Respondent 4] • Like it because you can move it around easily and get all aspects of the specimen. More realistic than anatomy books. Labelled structures are very useful and you don't often have this on the plastinated real specimens. Useful labels and information is just a mouse click away [Respondent 5] • I think it would provide a good way to learn anatomy without only relying on textbooks • Allowed me to visualise anatomy in real time and would be a great learning tool [Respondent 6] • Able to relate movements to muscles. Exciting tool for both learning and the clinic. The future is now [Respondent 7] • Being able to use AR as a learning tool is a brilliant idea [Respondent 8]	There was increasing evidence that this approach of teaching anatomy is innovative and unique.

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