EasyChair Preprint

№ 5220

Validation of an Inverse Kinematic VR Manikin in Seated Tasks: Application in Ergonomics Training

Mohammad Homayounpour, Dorien Butter, Saaransh Vasta and Andrew Merryweather

March 24, 2021

Validation of an Inverse Kinematic VR Manikin in Seated Tasks: Application in Ergonomics Training

Mohammad Homayounpour[1], Dorien Butter[1], Saaransh Vasta[1],

and Andrew Merryweather[1]

[1] University of Utah, Utah, SLC 84112, USA
mo.homayunpour@gmail.com

Abstract. Lower back and neck pain are common musculoskeletal disorders (MSDs) among dentists and dentistry students. Increased awareness of ergonomics during job tasks could help to reduce MSDs. Virtual reality (VR) enhanced dentistry training programs are gaining popularity in academia. Quantifying inverse kinematics (IK) using VR manikins that mimic a user's body can inform ergonomic risk evaluations. We calibrated and investigated one of the IK manikins' accuracy compared to motion capture (MoCap) using a novel method. We show that posture estimation using VR is accurate to less than 10 degrees in 81% of the seated pick and place tasks for the neck and trunk angles. These results suggest that an accurate estimation of posture in VR is achievable to inform real-time postural feedback. This postural feedback can be integrated into VR enhanced training for dental students to help reinforce ergonomic posture and safer movements.

Keywords: Posture Estimation, Ergonomic Training, Virtual Reality, Inverse Kinematic, Motion Capture

1 Introduction:

Musculoskeletal disorders (MSDs) negatively affect dentists worldwide and are even reported among dental students [1, 2]. The most prevalent regions for pain in dentists and dental students are the neck (19.8–85%) and back (36.3–60.1%) [2]. Awkward static postures and poor workplace practices are two main risk factors in developing MSDs in dentistry [2]. One strategy to reduce low back pain (LBP) and neck pain (NP) in dentistry students is providing just-in-time intervention (JITI) to reinforce proper ergonomic posture while learning a new skill. One crucial factor in helping people maintain a proper ergonomic posture and prevent MSDs is incorporating ergonomic principles into job training from the first day. Ergonomics training at the workplace shows higher behavioral translation levels and has lower musculoskeletal risk in an office environment [3]. Therefore, ergonomics training plays a critical role in preventing the risk for LBP and NP, and needs to be incorporated into dentistry curricula from the very beginning with the help of new technologies.

Virtual Reality (VR) is emerging as a new tool to train and educate workers and students across many disciplines [4]. VR training aims to create realistic and safe workplace experiences that allow users to learn how to avoid risks and apply ergonomics while working in demanding environments [5-7]. VR simulation and training have become a popular pre-clinical training tool in dentistry schools worldwide, and the results have been promising [8, 9]. Such training helps students develop their technical skills without the expenses and risks associated with dental models or patients.

VR systems are capable of solving for inverse kinematics (IK) using tracking data. Head-Mounted Displays (HMD), controllers, and Vive Trackers provide accurate position, orientation data, and latency are well within the margins of error compared to the data obtained from Mocap [10, 11]. The position and orientation data allow for developing a manikin inside VR by solving the IK to represent the user's movement and posture [12-14]. While increasing the number of trackers can improve the IK's accuracy, it will decrease user comfort and increase setup time and cost. Multiple groups have proposed IK manikins within VR [12-14], but the model's accuracy has only been validated qualitatively through questionnaires [12, 13] or by comparing the position and orientation of the end effector, not the joint angles [13]. To date, no methods have been proposed to validate these IK manikins quantitively using joint kinematics. Validation is critical to the further development and implementation of postural estimation in VR for ergonomics training.

Although MoCap systems can provide us with the most accurate kinematic tracking, its applications are mostly limited to research environments. In contrast, VR systems are not as accurate as MoCap but can solve for IK outside of research environments without the complexity and cost. This study aims to evaluate the IK manikin's accuracy in estimating the user's neck and trunk posture during sitting tasks. We propose a novel method to quantitively measure the error in the estimated joint angles compared to a motion capture system (gold standard). Accurate posture estimation in VR would allow integrating postural feedback and ergonomics to VR training among dentistry students to encourage ergonomic behavior and identify hazardous movements.

2 Methods:

Participants were recruited under the University of Utah Internal Review Board (IRB: 126927) protocol without any exclusion criteria.

2.1 Test procedure:

Participants were instrumented with 29 retroreflective MoCap markers to track the head, trunk, pelvis, and arms (Vicon, Nexus). Participants were also fitted with a Valve Index Head Mounted Display (HMD), two Valve Index controllers, three HTC VIVE Trackers, placed on the lumbar spine (hip), and both feet (Fig. 2). IK manikin using Final IK (ROOTMOTION) asset was used in Unity to mimic the participant

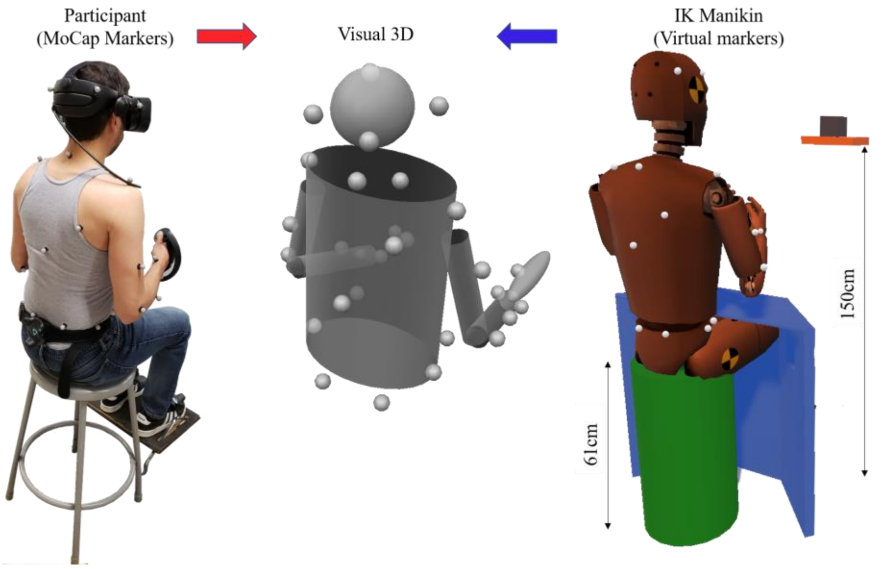

Fig. 2: Experimental setup. The upper body markerset was placed on the participant, and the same markerset was applied to the manikin in VR. Marker data from both the motion capture system and VR were imported to V3D to calculate the trunk and neck angles.

posture. Virtual markers on the IK manikin modeled the MoCap markers on the IK manikin. The IK manikin size was uniformly calibrated based on a participant's stature. Then the participant was asked to sit on the stool and look forward. The orientation of the head was corrected in this position. After that, the participant was asked to start neck flexion to adjust the hip tracker's position on the IK manikin. This adjustment was performed to achieve straight back on the IK manikin when they looked straight, and the hip was not lifted when they performed neck sagittal flexion visually.

After calibration, participants were instructed to pick up a virtual box (10x10x10cm) from a shelf (*h*=150cm), and reach over a trapezoidal desk, Fig. 1, to place the box in one of three holes (right, middle, and left). Participants were instructed to only use their right hand. This task was repeated 15 times for each hole. This protocol was selected to maximize the range of motion (ROM) in the lower back and neck.

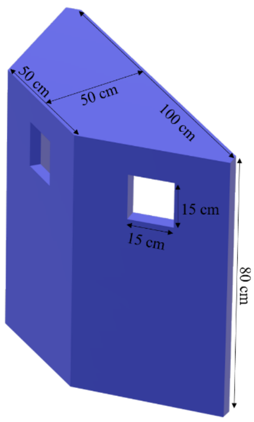

Fig. 1: Table dimensions in the setup.

2.2 Data analysis:

Virtual marker data were converted to text files, mimicking MoCap file extension. The VR coordinate system was aligned with the MoCap's coordinate system, and the data were exported to Visual 3D (V3D) for kinematic analysis. A V3D model was created based on the markerset to calculate the neck and trunk angles. The same model was applied separately to both the virtual markers and MoCap markers for each participant. The trunk angles were calculated with respect to the lab coordinate system, and neck angles were calculated with respect to the trunk. "Pick" and "Place" events were defined for each trial based on markers' position. Pick event was the moment the subject grabbed a new box and was defined as 90% of the maximum height of the right finger marker. Place event was the moment the subject placed the box in the designated hole, and was defined as the minimum height of the right finger marker. All trials were normalized from Pick to Place from 0 to 100%. MATLAB 2020a (MathWorks, Natick, MA, USA) software was used for statistical analysis and plots.

2.3 Statistics:

Cross-correlation (Corr) and root mean square error (RMSE) were calculated on the normalized trials from Pick to Place, comparing the virtual markers (IK manikin) to the MoCap calculated angles. The trials were divided based on whether the box was placed in the right, middle, or left holes. Linear mixed models were used to estimate angles for neck and trunk at Pick and Place for each trial by assigning the source of the data, VR and Mocap, as the fixed factor and participant as the random factor.

Results:

Six participants, four females and two males (age 24.9±3.2 y.o (mean±Std.), height 175.2±8.2cm, and weight 73.1±7.2kg) were tested. The neck and trunk maximum ROM, across all trials, were 45 and 54 degrees in sagittal flexion, 34 and 89 degrees in lateral flexion, and 46 and 90 for axial rotation, respectively. The IK manikin closely followed the movement trajectory of the participant in all the trials, Fig. 3. The mean(Std.) cross-correlation coefficient and the respective RMSE of all trials are reported in Table 1. The cross-correlation reported for the neck and trunk were higher than 0.88, and the mean RMSE was within 11.8 degrees in all pains of motion. The neck and trunk angles at Pick and Place for the right, middle, and left trials are report-

Table 1: Average of Cross-Correlation (Corr) and root mean square error (RMSE) values in degrees for the neck and trunk angles.

	Sagittal Extension		Lateral Flexion		Axial Rotation	
	Corr	RMSE	Corr	RMSE	Corr	RMSE
Neck	.90(.19)	6.7(3.9)	.91(.19)	6.6(5.1)	.93(.12)	11.8(10.7)
Trunk	.99(.03)	9.3(3.5)	.89(.25)	4.6(3.3)	.88(.20)	9.9(5.7)

ed in Table 2. The VR system estimated the angles within 5 degrees of error in 17 out of 36 reported events. The mentioned errors were within 5 to 10 degrees in 12 out of 36 reported events and greater than 10 degrees in just 7 events.

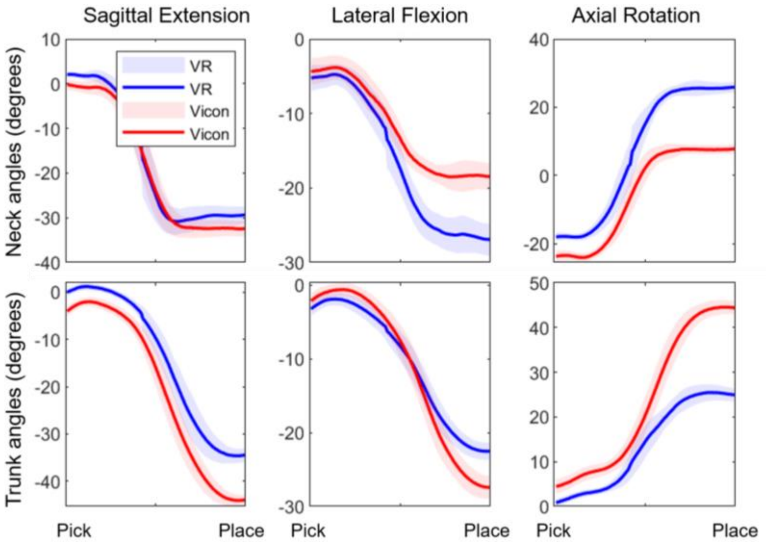

Fig. 3: The mean and Std. of neck and trunk angles from Pick to Place for the left trials.

Table 2: Neck and trunk angles (mean(SE)) measured with the VR system vs. MoCap (ground truth). The sagittal extension, lateral flexion and axial rotation are reported at the time of Pick and Place for the right, middle and left trials.

			Sagittal Ext.		Lateral Flex.		Axial Rot.	
			Pick	Place	Pick	Place	Pick	Place
Right	Neck	VR	-7.6(2.9)	-34.3(3.1)	1.6(1.7)	18.0(1.6)	-15.8(2.5)	-26.0(1.9)
		MoCap	-3.8(0.8)	-23.8(0.7)	4.0(0.5)	19.3(0.6)	-20.6(0.7)	-29.1(0.7)
	Trunk	VR	-1.1(0.7)	-26.1(1.8)	-2.6(0.8)	23.5(1.7)	-7.3(2.1)	-14.8(1.1)
		MoCap	-6.6(0.5)	-34.9(0.5)	-1.9(0.3)	31.6(0.4)	-3.5(0.4)	-18.2(0.6)
Middle	Neck	VR	-6.0(3.7)	-37.0(2.7)	-2.0(1.4)	-10.5(1.3)	-9.3(1.3)	5.0(1.9)
		MoCap	-4.0(0.8)	-30.8(0.6)	0.9(0.5)	-1.9(0.5)	-16.2(0.6)	-5.7(0.5)
	Trunk	VR	-0.7(0.9)	-37.9(3.0)	-3.5(0.6)	-3.4(0.9)	-5.3(1.6)	-1.7(1.6)
		MoCap	-6.2(0.5)	-49.3(0.7)	-2.5(0.2)	-1.6(0.6)	-0.7(0.4)	7.9(0.6)
Left	Neck	VR	-6.6(3.4)	-25.3(1.5)	-4.2(1.2)	-25.3(3.1)	-11.5(2.6)	31.1(2.0)
		MoCap	-4.0(0.8)	-26.5(0.8)	-1.0(0.6)	-17.3(1.7)	-17.7(1.9)	14.7(2.3)
	Trunk	VR	0.9(1.3)	-29.5(1.9)	-4.2(1.1)	-23.4(1.7)	-1.2(1.4)	16.2(2.5)
		MoCap	-5.2(0.4)	-40.6(0.8)	-3.2(0.3)	-30.1(0.9)	4.7(0.5)	38.5(0.6)

Errors < 5 degrees
5 < Error < 10 degrees
Error > 10 degrees

3 Discussion:

We tested the accuracy of the IK manikin quantitatively using a novel method through V3D for estimating the neck and trunk angles in a sitting task. The IK manikin estimated the neck and trunk angles within 10 degrees of error in 81% of the measured events across different tasks. It has been reported [15] that human error in ergonomic assessments, such as rapid upper limb assessment (RULA), was within 10 degrees for neck and trunk angles; therefore, the reported IK manikin accuracy is within an acceptable range to be used for ergonomic assessments. The IK manikin could be integrated into dental VR training and warn the trainee if they do not maintain an ergonomic posture.

The accuracy of the estimated posture was variable based on the event. At the Place event, in trials where the errors were greater than 5 degrees, the neck angles were overestimated in the IK manikin to compensate for trunk rotation underestimation. The motion of reaching over a table and placing the box required rotations in both the thoracic and lumbar spine. This study only used one tracker on the lower back to minimize the complexity and cost (the feet trackers were not used during the sitting tasks). Since we did not have a tracker at the thoracic level, the rotation at this level was not captured by the IK manikin. As a result, the IK manikin compensated for that rotation by overestimating the neck angle. This compensation was most noticeable for trials where the block was placed in the middle and left holes. This error can be reduced by adding a tracker on the thoracic segment or moving the lumbar tracker to a higher level of the spine. Also, in many of the trials, although the IK manikin closely followed the MoCap data, there was an offset between the two systems, which may be corrected by optimizing the virtual markers' placement on the IK manikin.

These results highlight the potential to integrate postural feedback based on ergonomic principles into VR training, an essential step in preventing MSDs [6]. Integrated postural feedback can reduce the required one-on-one time between an instructor and user and increase training consistency, which is especially beneficial for dentistry curricula, demanding many hours of training. Furthermore, integrating an accurate full-body IK manikin allows users to have the same proprioceptive and visual feedback on their body positioning and posture and more immersion in VR [16], further reinforcing a more ergonomic posture.

For future work, we propose improvements in the IK manikin’s marker placement. This improvement can be made by minimizing the relative distances between the IK manikin markers and a MoCap markerset after the IK manikin is calibrated. This refined IK manikin may be used later as a tool to validate the other IK manikins in VR systems.

4 Conclusions:

This study proposed a unique method to quantitatively test the accuracy of a VR IK manikin with integrated inverse kinematics based on joint angles. We created a virtual markerset on the IK manikin and used it as an input to V3D to compute the neck and trunk angles during seated tasks representative of dental procedures. These results suggest that posture estimation can be integrated into VR training, and users should benefit from real-time feedback to reinforce ergonomic posture.

5 Acknowledgment:

This research was funded in part by grants from National Institute of Occupational Safety and Health (NIOSH) 5 T42OH008414-15-00 and R18HS025606 from the Agency for Healthcare Research and Quality (AHRQ). The content is solely the responsibility of the authors and does not necessarily represent the official views of the AHRQ or NIOSH.

6 References

[1] S. Vijay and M. Ide, "Musculoskeletal neck and back pain in undergraduate dental students at a UK dental school-a cross-sectional study," *British Dental Journal,* vol. 221, no. 5, pp. 241-245, 2016, doi: 10.1038/sj.bdj.2016.642.

[2] M. J. Hayes, D. Cockrell, and D. R. Smith, "A systematic review of musculoskeletal disorders among dental professionals," *International Journal of Dental Hygiene,* vol. 7, no. 3, pp. 159-165, 2009, doi: 10.1111/j.1601-5037.2009.00395.x.

[3] M. Robertson *et al.*, "The effects of an office ergonomics training and chair intervention on worker knowledge, behavior and musculoskeletal risk," *Applied Ergonomics,* vol. 40, no. 1, pp. 124-135, 2009, doi: 10.1016/j.apergo.2007.12.009.

[4] B. D. Gasparevic, "Why Virtual - Reality Training for Employees Is Catching On," ed, 2019, pp. 3-5.

[5] X. Li, W. Yi, H.-L. Chi, X. Wang, and A. P. C. Chan, "A critical review of virtual and augmented reality (VR/AR) applications in construction safety," *Automation in Construction,* vol. 86, pp. 150-162, 2018, doi: 10.1016/j.autcon.2017.11.003.

[6] R. Leskovský, E. Kučera, O. Haffner, J. Matišák, D. Rosinová, and E. Stark, "A Contribution to Workplace Ergonomics Evaluation Using Multimedia Tools and Virtual Reality," presented at the Proceedings of the 2019 Federated Conference on Computer Science and Information Systems, 2019.

[7] B. Hu, L. Ma, W. Zhang, G. Salvendy, D. Chablat, and F. Bennis, "Predicting real-world ergonomic measurements by simulation in a virtual environment," *International Journal of Industrial Ergonomics,* vol. 41, no. 1, pp. 64-71, 2011, doi: 10.1016/j.ergon.2010.10.001.

[8] I. Mirghani *et al.*, "Capturing differences in dental training using a virtual reality simulator," *European Journal of Dental Education,* vol. 22, no. 1, pp. 67-71, 2018.

[9] V. R. LeBlanc, A. Urbankova, F. Hadavi, and R. M. Lichtenthal, "A preliminary study in using virtual reality to train dental students," *Journal of dental education,* vol. 68, no. 3, pp. 378-383, 2004.

[10] D. C. Niehorster, L. Li, and M. Lappe, "The Accuracy and Precision of Position and Orientation Tracking in the HTC Vive Virtual Reality System for Scientific

Research," *Iperception*, vol. 8, no. 3, p. 2041669517708205, May-Jun 2017, doi: 10.1177/2041669517708205.

[11] S.-W. Choi *et al.*, "P-195L: Late-News Poster: Head Position Model-based Latency Measurement System for Virtual Reality Head Mounted Display," in *SID Symposium Digest of Technical Papers*, 2016, vol. 47, no. 1: Wiley Online Library, pp. 1381-1384.

[12] P. Caserman, A. Garcia-Agundez, R. Konrad, S. Göbel, and R. Steinmetz, "Real-time body tracking in virtual reality using a Vive tracker," *Virtual Reality*, vol. 23, no. 2, pp. 155-168, 2018, doi: 10.1007/s10055-018-0374-z.

[13] P. Caserman, P. Achenbach, and S. Göbel, "Analysis of inverse kinematics solutions for full-body reconstruction in virtual reality," in *2019 IEEE 7th International Conference on Serious Games and Applications for Health (SeGAH)*, 2019: IEEE, pp. 1-8.

[14] F. Jiang, X. Yang, and L. Feng, "Real-time full-body motion reconstruction and recognition for off-the-shelf VR devices," presented at the Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry - Volume 1, 2016.

[15] A. Golabchi, S. Han, A. R. Fayek, and S. AbouRizk, "Stochastic Modeling for Assessment of Human Perception and Motion Sensing Errors in Ergonomic Analysis," *Journal of Computing in Civil Engineering*, vol. 31, no. 4, 2017, doi: 10.1061/(asce)cp.1943-5487.0000655.

[16] M. Slater and S. Wilbur, "A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments," *Presence: Teleoperators & Virtual Environments*, vol. 6, no. 6, pp. 603-616, 1997.