Haptics enhanced multi-tool virtual interfaces for training carpentry skills

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Abstract— **This paper presents the design and computational modelling of a virtual simulator of a multitool, for training vocational skills in a hands-on way. Here we describe the audio-visual-haptic elements for the customized simulation interfaces for training carpentry tools and skills and the computational mathematical model to render haptic feedback for these actions. Finally the paper will explain the trainee's skill learning curves through these simulations, based on analysis of data from user studies. In our previous work, we designed a haptic training simulation interfaces for plumbing tools as part of Computerized Vocational Education and Training (CVET). As an extension to this we had developed a cost effective system to simulate various common tool exercises and procedures in virtual environments with a special focus of carpentry. Proposed system is designed to replace conventional training in the initial stage of vocational skill training and fasten the skill learning process to a diverse audience with varying skill sets.**

***Keywords*— Audio-visuo-haptics, carpentry skills, multi-tool simulators**

I. Introduction

Education, skill development and technical training prepares a mostly young workforce in the formal and informal sectors in rural areas, and thus plays an important role in poverty reduction. Better training will refine skills, raise income and improve rural livelihoods [1]. Vocational Education and Training (VET) holds the potential to enrich the socioeconomic development of the impoverished communities resulting in a better quality of life, especially in developing countries [2].

In the developing world, VET is paralysed by many serious challenges like lack of sufficient VET schools, expert skilled trainers, raw materials, funds for necessary equipment, and social stigma[3]. These issues contribute to limited scalability in the mainstream labour sector and high unemployment, which creates the need for cheap, sustainable approaches to vocational training [4]. Impoverished populations have limited time to devote to the traditional model of education system suffers knowledge transfer stagnation [5]. Hence, it is essential to develop systems with self paced learning. Consequently, CVET holds for the potential, scalable, portable and affordable solution to provide training to the unskilled population, especially in remote areas [6].

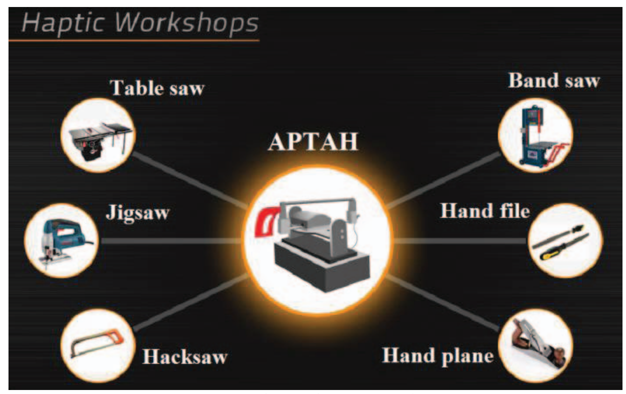

Fig.1 Multi-tool VET simulator.

Audio, visual and haptic sensory combined VR systems can be efficiently used to train students in technical procedures [7], medicine [8], military strategy [9], occupational skills [10], academic contents [11] etc. Morris et al. [12] have discussed the advantages of visuo-haptic training applying to force skill learning and Sewell et al. [13] analysed the transference of motor skills learned in a haptic-enabled virtual environment to performance. Haptic simulation for VET is an underdeveloped area of research in the simulation-training domain. Very limited reported work designed applications enriched with touch and gesture based technology to train operators of numerically controlled milling machines[14], welding[15], soldering[16] and fabric painting[17][18].

Karahoca et al. [19] created an interactive e-learning tool for teaching vocational education providing computer parts and assembly instruction. Bhavani et al. [20], adopted an innovative multimodal based learning approach to deliver vocational education for semi literate people in rural India. Previously we have created the TryStrokes application to teach painting skills using Wacom tablet and stylus in the context of fabric painting[18].

In the interest of incorporating hands-on training in tool usage into the CVET model, we designed the APTAH (Amrita Progressive Training Assistance using Haptics) simulator. It is a cost-effective, multi-tool haptic simulator that can train the use of 19 hand-held and power tools. These tools are used in various vocations. The APTHA tool could replace conventional training in the initial stage of

978-1-5090-5203-5/16/ $31.00 ©2016 IEEE

vocational skill training[21]. Previously we developed virtual haptic simulators for training plumbing skills and tools using custom made haptic device APTAH [22]. As an extension of this work, this paper describes the design and analysis of new multi-tool virtual training interfaces for various vocational tools and scenarios, with a special focus on carpentry as shown in Fig. 1.

The proposed virtual reality (VR) model provides audio, visual, haptic and performance feedback to the trainees, offering a realistic experience of a vocational workshop training session. This offers an improvement of skill learning when compared with traditional means of training. Introducing haptics in VET opens possibilities to provide the standard performance, evaluation benchmark and standardization in workman ship. It can also glamorize vocational training, and thereby attract more candidates. The paper is organized as follows: section 2 describes the design of the proposed system, section 3 explains the haptic computational model for simulations and section 4 summarises the evaluation results.

II. SYSTEM DESIGN

Proposed system comprised of a audio, visual and haptic display interfaces built on open source Chai3D haptic API with OpenGL and QT, connected to APTAH simulator with detachable handle. The system provides training for carpentry tools and skills with detailed skill evaluation matrix.

A. Basic User Interface frame

Fig.2 General UI elements in training simulation.

A basic User Interface(UI) frame is designed for all proposed simulations in the carpentry training simulator as shown in Fig. 2. All the common UI elements, buttons, visual cues are arranged in a simple manner to aim for a semi literature audience. Trainee can select different types of wood for cutting(Teak, Mahogany and Jackwood) from the Wood Menu, and reset the broken blade of the tool by New Blade button available on the left side of the UI. A Pressure Indicator available for the downward pressure exerted by the user through the Aptah device, marked 'L', 'M', and 'H' indicate Low, Medium and High pressures respectively.

A set of Navigation and Zoom buttons is used to change the camera view, which gives user a complete 360 degree view of the simulation. Timer indicates the time elapsed to complete the task and Reset button helps to reset the simulation exercise. Set of Arrow buttons used to adjust the stopper, wood & blade models.

B. Carpentry training simulations

Here we developed a multi-tool training simulator for carpentry tools with simulation interfaces of Bandsaw, Jigsaw, Table saw & Hand plane as shown in Fig. 3 for wood cutting and planing exercises. The respective tool interfaces together offer a set of exercises used in training student carpenters to cut wood pieces using different cutting tools and then plane it down as needed. The virtual workshop atmosphere integrates the visual, audio and haptic interactions between the 3D virtual models of tools and materials. The trainee can select the job material, tool type, and then control the virtual tool using the haptic simulator. The haptic simulator provides the trainee with accurate force feedback, vibrations and the feel of using the actual tool computed by the computational model explained in section 3. All the variables accounted for a conventional wood cutting training exercise were replicated in the simulation interface.

Step by step instructions to the trainee by audio and text messagesdisplayed on the screen made trainee ready for the exercises. Trainee can align the work piece and blade using visual cues like red to green cut mark. Push the virtual tool/work piece towards cutting mark by slowly pushing the wooden handle of the Aptah device in the forward direction applying a downward pressure. A hand plane is a manual tool used for flattening and smoothing rough wood. A red 'Guiding plane' is used to train the speed of the hand plane as shown in Fig. 3d. Move virtual hand plane by moving the Aptah device forward and backward to match the speed of the 'Guiding Plane'. Downward pressure applied by the trainee on the hand plane is tracked by the device and shown to trainee by pressure indicators in the UI.

Power tools are very dangerous devices to handle. Certain precautions need to be taken while handling the tool. Kickback happens when the blade catches the workpiece and violently throws it back to the front of the saw, towards the operator and can injure the operator. Kickback happens when ripping if, the wood approaches the blade very quickly and not applying sufficient downward pressure on the wood. This is difficult to predict and can be impossible to control when using fingers to hold the wood down. For safety training, the simulator replicates the error cases and train the user on handling & avoiding error cases. The wood is allowed to raise up or moved sideways during a cut, then pushed back down, taking too big a bite at the top of the blade. This can be prevented by using substitutes for fingers like feeder wheels and push sticks very close to the start ofthe blade and hold downs after the blade to control the wood all the way through the cut.

After each exercise, a detailed evaluation page is displayed, showing the Procedural flow, Straightness of cut, Stroke velocity, Speed of cut, Broken blade count, Average applied pressure, safety skills and an aggregate final score for the exercise based on these variables. Depending on the wood material selected and length of the required cut, haptic feedback provided to the trainee varies in magnitude.

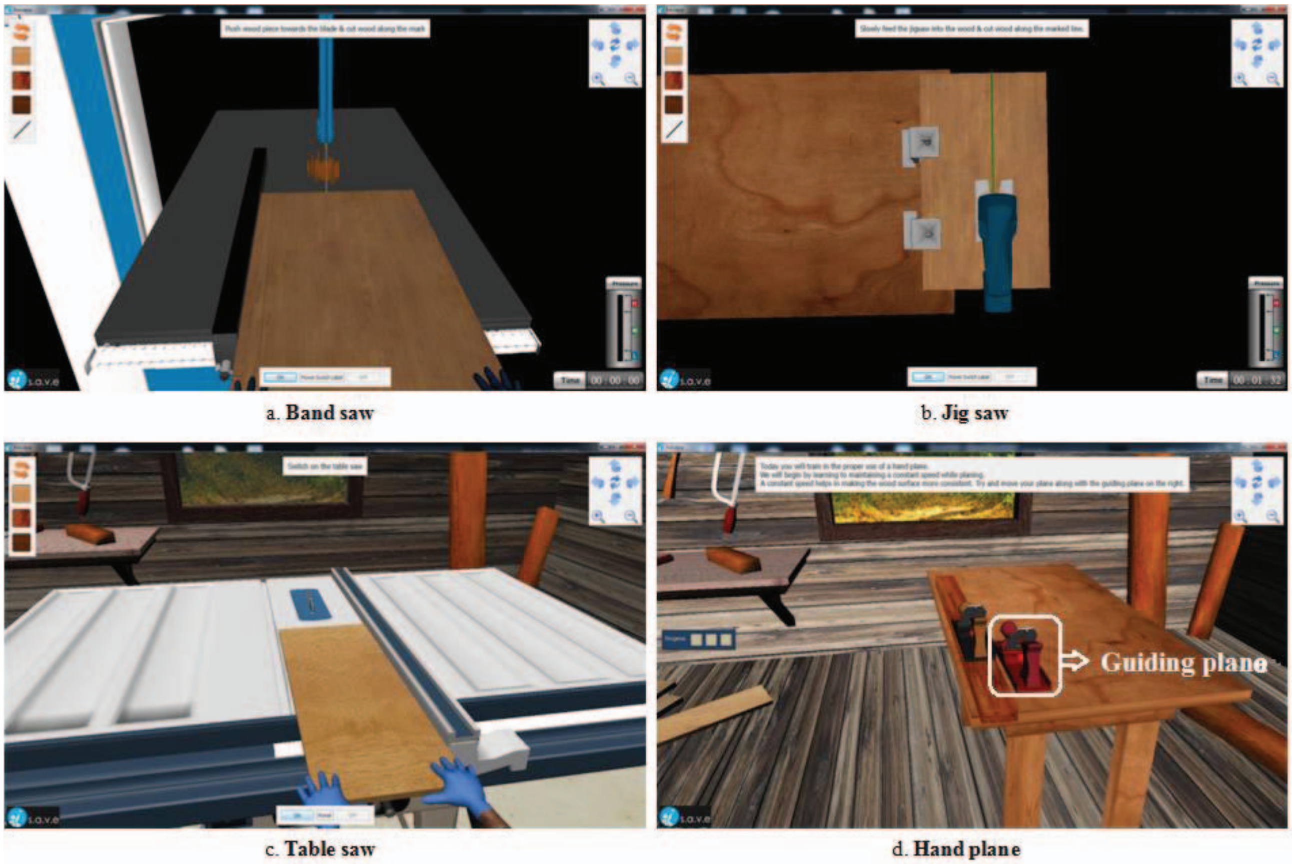

Fig.3 Carpentry tools training simulation user interfaces.

C. Wood models

We selected three types of wood models as work piece, which are Teak, Mahogany and Jack wood are commonly used for furniture and cabinets. Teak (Tectona grandis) wood is moderately hard and moderately heavy(650 kg/m3 at 12% moisture content) with coarse texture and high strength. Modulus of Rupture (MOR) is 106kg/mm2 and Maximum Crushing Stress(MCS) is 60.4kg/mm2.The difficulty level for cutting is high compared to the other two woods. Mahogany (Swietenia macrophylla) is moderately hard and moderately heavy(650 kg/m3at 12% m. c.) with medium to coarse texture and high strength. MOR is 83kg/mm2 and MCS is 44.2kg/mm2. Jack wood (Artocarpus heterophyllus) is a moderately soft wood (555 kg/m3 at 12% m.c.) with coarse to medium texture. MOR is 8.06kg/mm2 and MCS is 4.96kg/mm2 [23]. So it is easy to saw and work, can be brought to a smooth finish. In the simulation, we designed Teak as a hardwood, Mahogany as a medium hardwood, Jackwood as a softwood using the haptic & graphic properties for these wood models.

D. Haptic device and force feedback

APTAH [21] is a custom made cost effective multi-tool haptic simulator that can train the use of 19 hand-held and power tools used in several vocations. The trainee can feel the force feedback and vibrations from the virtual training interface with the help of the haptic simulator APTAH, which consists of one active translational and three passive rotational degrees of freedom along the yaw, pitch and roll axes. APTAH has interchangeable handles and uses different VR interfaces to simulate different tools.

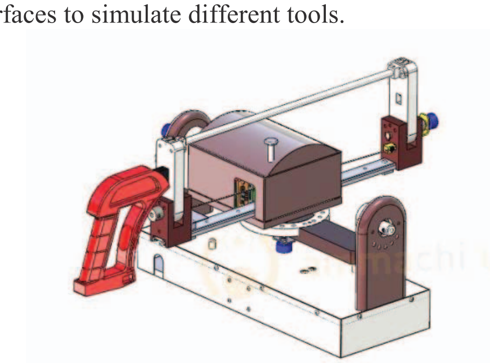
Fig.4 APTAH haptic device for multi tool training simulator.

Two kinds of haptic feedback effects are provided: linear force feedback and vibratory feedback. Linear feedback is achieved using a brushed DC maxon motor producing a maximum force of 40.22 N at the end effector. Vibratory feedback is produced by vibratory motors placed in the handles of the simulator. The simulator moving position can be categorized in three states: at rest (v = 0), moving forward (+v,) and moving backward (–v). The force feedback algorithm receives tool position, collision detection, downward pressure, yaw, pitch and roll from the haptic simulator through the Ethernet communication driver. The effective force parameters and feedback are calculated using the computational model explained in section 4 and sent back to the simulator with a 1000Hz update haptic rendering loop, which generates forces using these parameters, providing the trainee with kinesthetic feedback of the haptic simulation.

III. Haptic Computational model

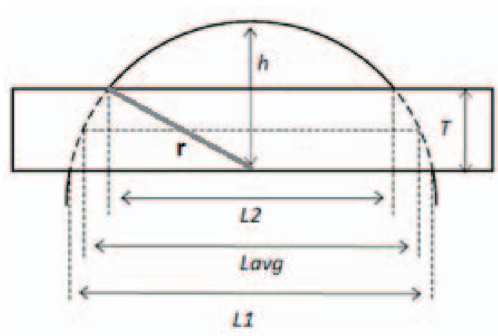

Fig.5 Side view of blade- work piece contact .

The computation model covers progress of a cut in terms of sawing forces, torques applied by a trainee and haptic feedback needed from the device to enable effective training simulations for carpentry power tools. It addresses the force feedback from the resistance to the forward sawing motion. It also describes how yaw torque curves the cut, and how external forces and torques affect the cutting rate. Here we consider ideal cut contact as shown in Fig. 5 with a circular blade of radius r and a work piece material with weight w and thickness T. Here the x-axis is defined as forward-backward, the y-axis as right-left, and the z-axis as up-down, with the positive directions mentioned first in each case. Roll(γ) is taken about the x-axis, Pitch(β) about the y-axis and Yaw (α) about the z-axis.

Cutting rate depends on the forward force applied by the trainee is $\frac{\Delta x}{\Delta t} = \frac{k_C}{T} F_f min\left(1 - \frac{F_f}{F_{Cmax}}, 0\right)$, where k_C is a constant, F_f is the forward force applied by the traineeand F_{Cmax} is the maximum possible force feedback in the cutting direction. Audio and vibration feedback are also designed to reflect the cutting rate.

Force feedback F_c along the cutting direction(x-axis) is proportional to the downward force (F_D) applied to the work piece or saw by the trainee, resulting from the friction of the work piece and saw as it slides along the cut in contact with the work piece material. Once the cut has curved, there will be added friction from the blade being trapped in and squeezed by the curvature of cut. The effect is increased for a deeper cut, because of the associated increase in average length of blade in contact with the materialL_{avg}. So Force feedback is $F_c = \mu_c(F_D + w) + k_T T + \frac{\Delta\alpha_L}{\alpha_{max}} k_f L_{avg}$. The constants μ_c , k_T and k_f should be scaled to keep F_c below F_{Cmax} . Where $\Delta\alpha_L$ is the total change in yaw of either side during the last L distance of travel along the cut. α_{max} is the maximum allowed $\Delta\alpha_L$, which depends on the stiffness of the blade. Initially, we can set $\alpha_{max} = \alpha_0$.

Force feedback along the y-axis (side-to-side) $F_y = min\left(\frac{l}{l_0} F_{ymax}, F_{ymax}\right)$ should be zero at zero cut length (before the saw begins cutting), then increase to F_{ymax} (the maximum the hardware can provide) as the cut lengthens. It should reach F_{ymax} by the time length of the cut l reaches some critical value $l_0 = 3/16$, which was found experimentally.

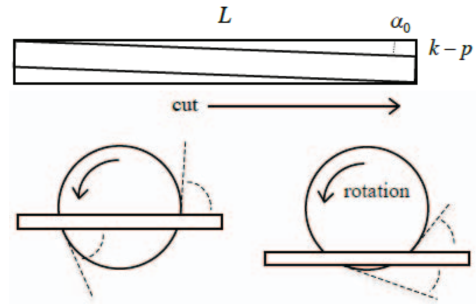

Fig.6 Free side yaw angle

As shown in Fig. 6, the free yaw rotation angle is approximately$\alpha_0 = \frac{k-p}{L}$, where p is thickness of blade and k is width of cut. Beyond this angle, there should be torque feedback resisting further rotation of the work piece. The feedback torque should match the torque applied by the trainee. If the trainee overrides the feedback, there should be a dramatic slowdown in the motor sound and vibration, and an equally dramatic slowdown in the cutting rate. We will assume the curvature of the cut to be limited to α_{max} per length L of travel along the cut. The rate of change of the yaw angle $\Delta\alpha$per change in forward motion along the cut Δx_f is then $\frac{\Delta\alpha}{\Delta x_f} = \frac{k_\alpha \tau_{\alpha applied}}{{L_{avg}}^2} max\left(1 - \frac{\Delta\alpha_L}{\alpha_{max}}, 0\right)$, where $\tau_{\alpha applied}$ is the applied yaw torque.

IV. Experiments, Evaluation & Results

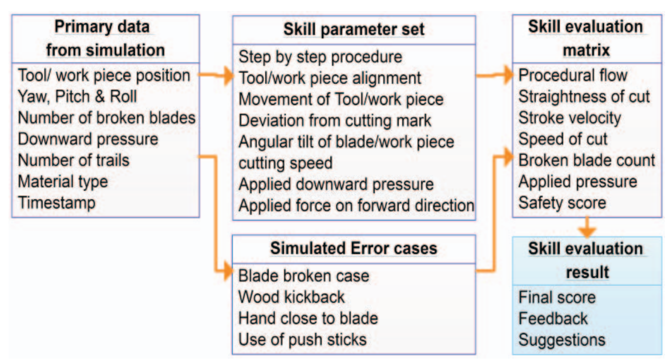

Table1: Skill parameter set

The simulation captures the primary data like tool/work piece position, downward pressure, no of trails and broken blades. Using these primary dataset simulation intelligence compute trainee's procedural flow, kinaesthetic skills including straightness of cut, stroke velocity, speed of cut, applied downward force, deviation from cutting mark, no of broken blades, angular tilt, time taken and safety skills

User type	Subject count	Wood type	Average score(out of 5)					Improvement (%)	Standard deviation
			Trial 1	Trial 2	Trial 3	Trial 4	Trial 5		
Novice	10	Jack wood	1.09	1.52	2.29	2.96	3.77	53.6	1.08
Novice	10	Mahogany	1.33	1.73	2.47	3.24	3.63	46	0.97
Novice	10	Teak	2.06	2.33	2.86	3.6	4.12	41.2	0.86
Experts	2	all 3	2.86	3.29	3.71	4.29	4.67	36.2	0.73

Table 2: Skill learning evaluation of experts vs. novices

User (novices)	Skill set	Average score(out of 5)					Improvement (%)	Standard deviation
		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5		
10	Procedural flow	2.03	2.43	3.20	3.80	4.20	43.4	0.91
10	Straightness of cut	1.37	1.93	2.47	3.23	3.63	45.2	0.92
10	Stroke velocity	1.37	1.67	2.17	2.80	3.37	40	0.82
10	Speed of cut	1.47	2.13	2.27	3.27	3.77	46	0.93
10	Broken blade	1.13	1.53	2.30	2.97	3.73	52	1.05
10	Applied pressure	1.40	1.50	2.60	3.27	3.97	51.4	1.11
10	Safety skills	1.67	1.80	2.77	3.53	4.20	50.6	1.09

Table 3: Vocational skill curve.

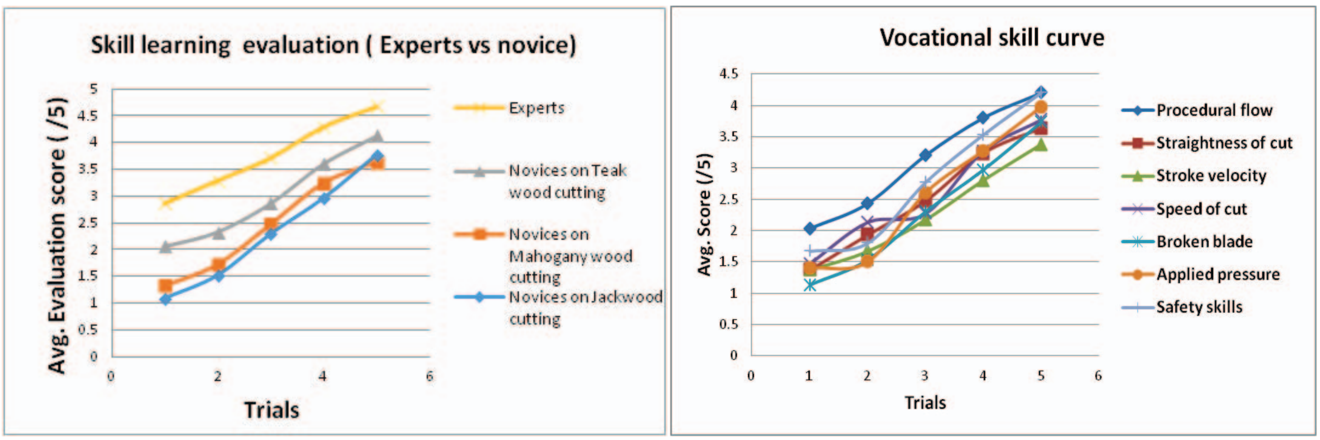

Fig.7 Experimental result plots

shown in Table 1. Our model incorporates common error cases, and educates the trainee on safety features of the respective tools as well as safe practices. Using error cases and safety procedures, the simulation provides the requisite safety skill training for the vocational industry.

A preliminary user study was conducted to study how effectively the simulator could train a person in using a particular tool or skill in vocational education and training. This user study validated the designed simulator can produce a measurable difference between participants with varying levels of expertise in vocational skills. Experiment set up of our simulator consist of two modes, training mode and evaluation mode. In training mode, the simulation provides step-by-step procedural instructions and the skill variables are matched against the pre-recorded expert's data and corrected by real-time audio-visuo-haptic feedback and graphical cues. When the trainee has completed the training mode, the simulation moves on to an evaluation mode, in which the simulation doesn't provide any audiovisual guidance or graphical cues.

Two experts were asked to cut the virtual wood piece in all the simulation interfaces of four tools using APTAH and their skill data was recorded and kept as an evaluation reference. 10 novice users were first given wood cutting training in training mode of simulation and moved to evaluation mode. The skill parameters as shown in Table 1 equivalent to the quality of each cut across 5 trials were noted on each tool and wood combination exercises. These parameters are what is typically noted to evaluate one's skill with a carpentry tool. After every trial their data was compared to that of the experts and their performance was evaluated. Average evaluation score of each skill on each trial and final score on each sessions are computed from the tracked skill data matrix as shown in Table 2 and 3. The percentage of improvement on skill learning through proposed simulation was calculated by comparing the mean evaluation score on the last trial and first trial.

Analysis of evaluation results shows the validity of multi-tool, multi-skill training simulators for vocational skills. All sessions showed improvements with vocational wood cutting exercises with the simulator interfaces. Overall all sessions shows significant increase in learning scores and improvement in learning carpentry skills. Mean skill learning curves of experts and novices are plotted over the 5 trials on each sessions as shown in Fig. 7. Novice group shows mean improvement is 46.94% with standard deviation(SD) 0.97 as experts shows 36.2% with SD 0.73. Analysis showed significant improvement (>50%) with safety skills and sufficient downward pressure applying skills on reducing error cases like blade broken, wood kick back etc. Skills like procedural flow, straightness of cut and speed of cut improved by 43.4%, 45.2% and 46% respectively which also shows significant learning improvements.

V. Conclusions

In this work, we designed multi tool haptic training simulations for carpentry tools(both machine and hand tools) and evaluated its effect on skill learning improvements. Preliminary evaluation of haptic CVET simulations for carpentry tools showed that vocational trainers could successfully use this simulator as a bridge between theory class and hands on training. It can be used to teach the basic principles of carpentry training in safer conditions. It can also contribute towards solving some of the problems facing the field today, including: the dearth of trainers and classroom environments, limited availability of materials for practice and training, and the remote location of many prospective trainees. Also it shows its potential to track all skill parameters and provide feedback and suggestions to trainees which speedup the skill learning curve. Further, trainees get exposed to computers, broadening their horizons and instilling a sense of potential and self-confidence, which is of inherent value.

Acknowledgments

We wish to extend our sincere gratitude to Mata Amritanandamayi Devi, Chancellor, Amrita Vishwa Vidyapeetham for being an everlasting source of inspiration for our efforts. We also wholeheartedly thank the wonderful team at AMMACHI Labs for their support and encouragement and for providing constructive criticism and valuable inputs during the various stages of this work.

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