Evaluation of Hand-Tracking Systems in Teleoperation and Virtual Dexterous Manipulation

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Evaluation of hand-tracking systems in teleoperation and virtual dexterous manipulation

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***Abstract* — The quality of robotic dexterous manipulation, in real or in virtual environments, relies on a fine control of the fingertips to perform stable grasps and inside-hand manipulation. In practice, teleoperating a robotic hand requires to capture the human hand configuration. If the user manipulates objects with fingertips, the acquisition of their motion must be accurate enough to produce realistic manipulation at the robot hand or its virtual avatar.**

In this context, one challenge is to accurately capture the motion of the human hand. The performances of three different hand-tracking devices are evaluated in this paper: two data gloves, the VRFree and the Manus VR, and a vision-based system, the Leap Motion Controller. To this end, the positions of the human hand joints and fingertips are captured while performing several tasks, with a high-precision motion capture system as reference, and with the tested devices. The accuracy of the measured joint angles and fingertips positions is compared for the different systems. Specific measurement configurations are considered by varying the hand orientation and the distances to the sensors. The strengths and weaknesses of these different systems are deduced from the experiments. This system review gives insights into the relevance of hand-tracking devices for remote robotic or virtual manipulation.

Keywords — Manipulation, Dexterous manipulation, Inside-hand manipulation, Robotic hand, Grasp Quality, Data Glove, Teleoperation.

I. INTRODUCTION

The complexity of human hand enables dexterous movements and polyvalent uses. The human hand remains a source of inspiration and a reference to perform dexterous tasks, in real or virtual environments. Dexterous robotic hands have been developed to reproduce human dexterity. But the teleoperation of these robot hands, embedded on robot arms, is a key challenge.

Fig. 1: The teleoperated ROV with Technoconcept gripper © DRASSM

This work has been sponsored by the French government research program "Investissements d'Avenir" through the Robotex Equipment of Excellence (ANR-10-EQPX-44). It is also supported by the Nouvelle-Aquitaine Region (program "CPER Numeric" and "Psy-CoBot" project), in partnership with the European Union (FEDER/ERDF, European Regional Development Fund) and French National Research Agency (ANR) through the SEAHAND program (ANR-15-CE10-0004) and LabCom Mach4 (ANR-18-LCV2-0003).

As an example, in the Seahand ANR funded project [1], a robot hand is developed for submarine archeology purpose. The hand will be embedded on a Remotely Operated underwater Vehicle (ROV) and teleoperated from the boat to safely excavate delicate objects on shipwrecks. Fig. 1 presents the ROV used by the DRASSM (Department of Underwater Archeological Research of the Ministry of Culture in France) with a first gripper version. The remote control of a dexterous manipulation task with fingertips requires new high-fidelity teleoperation devices. Such hand-tracking devices should increase the realism of the immersive experience for the user.

To succeed in carrying out the work of an archaeologist diver, the robot must be able to reproduce the grasp taxonomy illustrated on Fig. 2. This figure presents human grasps and the associated grasps with the new Seahand robotic hand.

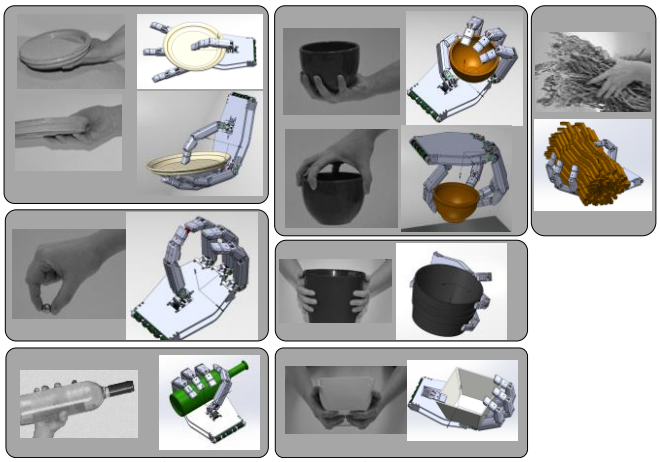

Fig. 2 An extract of the grasp taxonomy of the diving archaeologist – Human hand grasps versus Seahand robotic hand grasps

Many hand-tracking devices are existing on the market, but their performances were never evaluated in a scientific context. Most of these devices are designed to return the general shape of the hand and cannot provide a precise measurement of the joint angles or fingertips position. The Leap Motion Controller (LMC) has already been evaluated, but never compared with other devices. Moreover, the SDK (Software Development Kit) of the device called beta Orion, has been improved since the release of these studies. In the paper [2], a mannequin hand was used as a reference. In [3], the measures preformatted by the LMC are compared with Motion Capture measurement. In [4], the reference system in motion is an industrial robot. It is stressed in this paper that the uncertainty in measurement of the reference system must be at least in the magnitude of the natural

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tremor of a human hand, which is around 0.3 mm for a young person [5]. In [6], the authors study the accuracy of the LMC when measuring wrist and arm motions, in comparison with motion capture results. The LMC showed to provide good information when measuring the wrist flexion/extension, but not in pronation/supination of the forearm.

These papers show a good accuracy of the LMC measures in joint angles for a static hand ideally situated above the sensor. However, the measurement accuracy deteriorates when the hand is located far from the sensor. The performances of the LMC system were also inconsistent when measuring dynamic motions of the hand.

The literature review stresses that vision-based devices have to deal with visual occlusion, silhouette scales, hand appearance and unknown hand's morphology [7] [8] [9]. On another side, data gloves can be instrumented with a large variety of sensors including bending sensors, force sensors, accelerometers or gyroscopes. These sensors could improve the hand-tracking accuracy against vision systems. Due to hardware complexity, most data gloves are custom-made [10] and are difficult to use in robust industrial applications requiring accurate human hand tracking. Their implementation requests a laborious calibration process. The user's hand size and hand/glove positioning are a priori unknown and induces uncertainties [11]. Nonetheless, cheap hand-sensing systems recently reached the market equipped with Inertial Measurement Unit (IMU) and bending sensors.

In this paper, we present the analysis and comparison of three different systems measuring hand movements: two–data gloves and an optic based system. Section II first presents a state of the art of devices used for remote operation of robotic hands, then describes our test protocol for the evaluation. The experimental setup is introduced in section III. Section IV assesses the joint measurement performance of the three systems. Section V evaluates the quality of the measurement of the fingertip positions. Finally, Sections VI and VII are respectively devoted to the analysis of results and conclusion on the reliability and accuracy of these devices.

II. Hand-tracking systems for Remote Operation

Different systems can be used for remote control of a robotic hand. The use of joysticks is simple and intuitive, but these systems often have few degrees of freedom (dofs), which limits their use to remote operation of low-mobility grippers (open-close operation) such as [12] or the OCEAN ONE gripper [13]. The LMC is successfully used to remotely control grippers with few dofs (see [14], [15]). However, the lack of accuracy and reproducibility of the LMC joint measurements does not allow reliable control of systems with a higher actuation level–[16]. There are a few rare examples of remote operation of robotic grippers with a mouse and keyboard through dedicated software interfaces [17]. This solution allows a quick start even for novice people but provides a poor transparency and efficiency. The use of myoelectric signals measured at the level of the arm muscles is becoming more common. This method is mainly used for the control of medical prostheses, as in [18], but can also be implemented to control grippers [19], [20], [21]. However, this synergy-based method reduces the control flexibility, and prevents the independent control of the fingers.

Instrumented gloves are the most commonly used solution, thanks to its transparency and ergonomics. These systems can measure many hand movements and control complex grippers. They are intuitive, anthropomorphic and wearable, and provide a good transparency between the measurements made on the human hand and the instructions sent to the gripper. The CyberGlove glove is often integrated as it guarantees reliable measurement of all finger mobilities thanks to resistive bending sensors. For example, it was used to control the Robonaut's hand [22], [23], the DLR's hand [24], the Utah/MIT hand [25] and other anthropomorphic grippers [26]. However, users often encounter calibration difficulties with this glove. Several uses of the EXOS Hand Master instrumented glove [27] can be found in the literature. The glove measures the bending angles of the fingers through a parallel bar mechanism. This mechanism allows more accurate measurements but makes the glove less comfortable and hinders the natural motions of the human hand. Other instrumented gloves exist such as the VPL data glove [28]. But additional sensors are needed to measure all the desired finger mobilities.

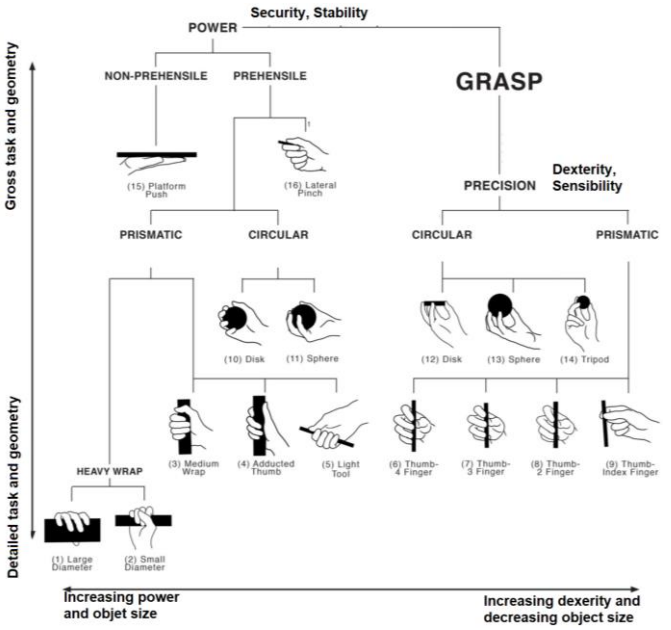

Fig. 3. The Cutkosky grasp taxonomy

In these literature examples, users have successfully teleoperated grippers. But, the accuracy requirement for this remote control was never mentioned, so as for the teleoperation device accuracy. Dexterous manipulation requires extended capabilities compared to simple power grasp. An under-actuated gripper, able to open or close its coupled fingers can produce stable grasp but not inside-hand or fine manipulation. Inside-hand manipulation requires precision grasp and a fine control of the fingertip positions. Moreover, we make a distinction between power grasps and precision grasps (Fig. 3) as described in the Cutkosky Taxonomy [29]. Power grasps consist in grasping an object with multiple finger and palmar contacts and do not require a high level of precision. Precision grasps, which are grasps with fingertip contacts, require the ability to precisely

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choose the localization of the contact point [30],[31]. The illustration of different grasps on Fig. 2. for the SeaHand project [1] includes both precision grasps and power grasps, as the object to be handled will come in a large variety of size, shape and weight.

To fill in this lack of precise evaluation the paper aims at quantifying the performances of three hand-tracking devices of different price ranges, one optic-based device, and two data gloves:

- The Leap Motion Controller (LMC) shown on Fig. 4 is a optic-based USB peripheral device equipped with two monochromatic infrared (IR) cameras and three IR LEDs to recognize and capture the position of the human hand. Due to its cheap price and ergonomics, this system is used in a wide variety of applications and commonly used to perform robotic hand teleoperation.

Fig. 4. The LMC with the motion capture markers

Many different data gloves exist, but not all of them are available on the market yet; and few of them are able to measure finger bending without any additional sensors. Their price can go up to $13,000 (for the cyberglove).

- The VRFree Glove (Fig. 5) is an instrumented glove developed by the Swiss company Sensoryx. It is now available for sale and is mainly used for virtual interactions in videogames. It is capable of measuring 21 dofs for the fingers and 6 dofs for the wrist (position and orientation), thanks to resistive bending sensors and several inertial measurement units (IMU). This glove is relatively cheap in comparison with other instrumented gloves.

Fig. 5. The VRFree Glove with the motion capture markers

We decided to evaluate that specific glove because of its price, and because it can measure all the needed dofs to teleoperate the Seahand robotic hand, particularly the abduction of the index and ring finger. Moreover, the sensing technology based on flexion sensors combined with inertial unit measurements is very typical, and it can therefore be assumed that its advantages and disadvantages will also be valid for other similar gloves.

We decided to evaluate another instrumented glove to observe the impact of sensor quality and glove finish on the quality of the measurements.

- The Manus VR glove (Fig. 6) is an instrumented glove developed by Manus VR, a Dutch startup. This glove is available for sale and is mainly used for several virtual reality applications. It can measure the flexion of the fingers, thanks to the resistive bending sensors. Only one additional IMU is attached to the thumb's proximal interphalangeal joint (PIP) to capture its orientation. The orientation of the palm is also tracked with an additional IMU.

We chose to evaluate this glove, prevalent in the virtual reality community, because of its ability of measuring many dofs of the human hand.

Fig. 6. The Manus VR glove with the motion capture markers

III. Approach to Assess the Measurement Quality of Three Hand-Tracking Devices

Our study goal is to evaluate the measurement accuracy of three hand-tracking systems: the VRFree glove, the Manus VR glove, and the Leap Motion Controller.

To this end, the hand-tracking measurements of the different systems are compared with measurements made in Motion Capture. The Motion Capture system Qualysis 7+ consists in several cameras recording the position of markers strategically placed on the user's hand. 16 cameras were used to capture the motion of the markers at a frequency of 100 Hz. The experimental set up is illustrated on Fig. 7. The resolution of the Qualysis system is 12MP. Given that the cameras are situated at a distance of 10 to 2 meters from the target, this resolution gives measurements with a margin error inferior to 0.4 mm. Since there are very few soft masses on the fingers and the joints are visible, it is easy to position the markers precisely and repeatedly. One individual placed all markers on the same subject for the three devices, for consistency. Markers were placed at both end of every phalanges of the hand. This marker-based Motion Capture method is proven efficient to capture dynamic movements of the hand [32] and can therefore forms the measurement reference. All measurements are done on the same user with a hand size suitable for the instrumented gloves.

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Fig. 7. Experimental set up

The markers are placed at the center of rotation of every finger joint to calculate the angles of flexion-extension and abduction-adduction (Fig. 8). The joint angles calculated in motion capture and obtained from the three different devices are compared. The precision of these measurements is evaluated while performing several gestures: random movement of the fingers, like a highly dynamic waving, and reproduction of the Kapandji test [33], that is to say successively touching the tip of the thumb with the tip of every other finger. The position accuracy on the thumb tip is evaluated while performing flexion-extension and adduction-abduction motions.

Fig. 8. Position of the markers on the hand

The robustness of the system is also evaluated according to the orientation of the hand and to the distance of the hand from the sensor.

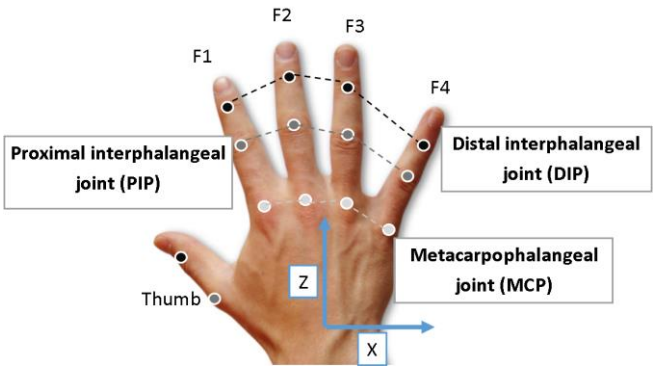

Fig. 9. Labeling of the finger joints

The ergonomic comfort and convenience of the different systems are discussed. The designation of the finger joints are summarized in Fig. 9: F1- Index finger, F2 - Middle finger, F3 - Ring finger, F4 - Little finger.

Standard deviation (STD) between the joint angle *j* measured with the device and the reference joint angle $jRef$ is calculated thanks to the following equation, where N is the number of measured points:

$$std = \frac{1}{N}\sqrt{\sum_{i=1}^{N}(j_i - jRef_i)^2} \quad (1)$$

In a first place, we will compare the joint angles obtained from the different devices, and then we will evaluate their precision in terms of fingertip position.

IV. Evaluation of the Angular Measure Precision

A. Random gestures for fingers F1, F2, F3 and F4

In order to evaluate the accuracy of finger bending measurements, the user performs random and natural finger flexions. Fig. 10, Fig. 11 and Fig. 12 show the Motion Capture reference joint angle in red and the joint angles obtained with each considered device in blue. Table I, Table II, and Table III summarize the mean STD angles of each joint for the four fingers.

1) The VR Free glove

As illustrated in Fig. 10 and Table I, the VRFree Glove is accurate when measuring large-amplitude flexion-extension motions but does miss small bendings, as the DIP flexion-extension motions. The measurement of the abduction-adduction motions lacks in precision.

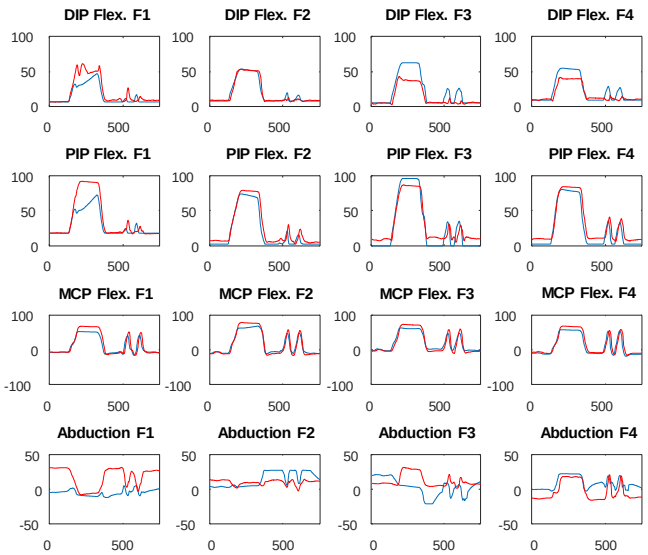

Fig. 10. Joint angles (deg) measured with VRFree glove (blue) and with the reference system (red) for a random gesture

Table I: STD angles for the fingers motions of random gestures measured with VRFree

STD DIP	STD PIP	STD MCP	STD Abduction
4.2°	8.1°	4.8°	15.1°

2) The Manus VR glove

Table II and Fig. 11 show that the measurements are quite

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reliable for the MCP flexion-extension motions of all the fingers. However, the glove presents some difficulties when measuring small-range flexion-extension motions: some of these motions are not detected, while sometimes their measured angles are far superior to the real bending angle.

Table II: STD angles for the fingers motions of random gestures measured with Manus VR

STD DIP	STD PIP	STD MCP
2.4°	10.1°	8.2°

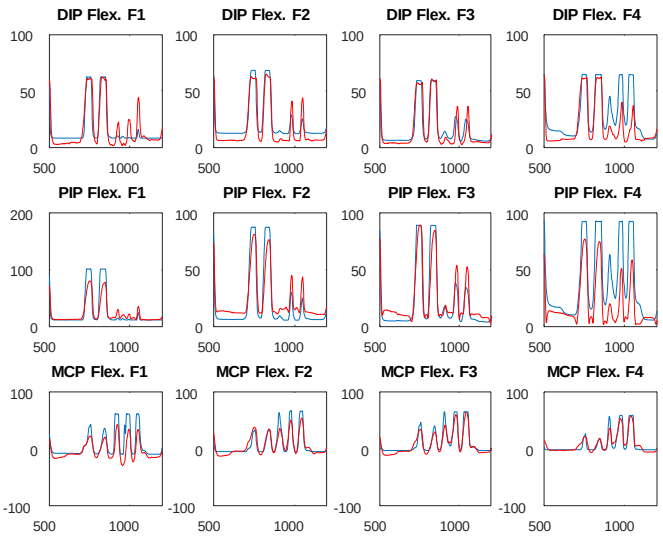

Fig. 11. Joint angles (deg) measured with the Manus VR glove (blue) and with the reference system (red) for a random gesture

3) *The Leap Motion Controller (LMC)*

It must be noted that the LMC gives us the guiding vector of the different phalanxes from which we calculated the joint angles.

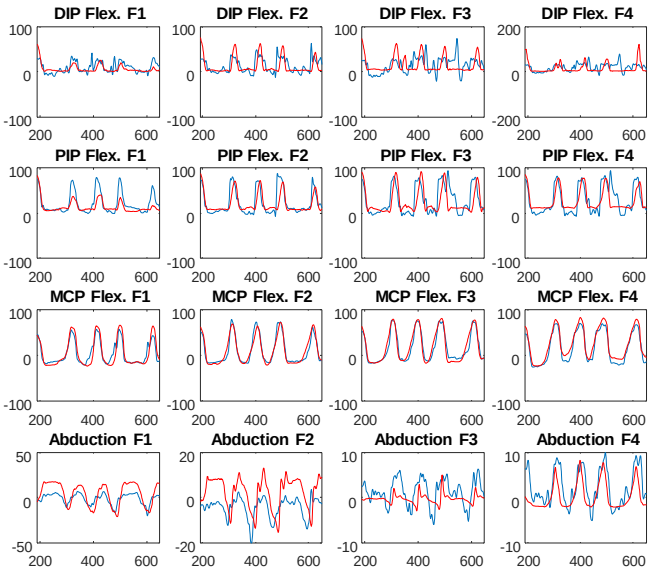

Fig. 12. Joint angles (deg) measured with the LMC (blue) and with the reference system (red) for a random gesture

As shown on Fig. 12 and Table III, the LMC provides very precise measurements of MCP flexion-extension motions but has a poor accuracy for the PIP and DIP flexion-extension motions. Moreover, it detects many non-existent gestures.

Table III: STD angles for the fingers motions of random gestures measured with VRFree

STD DIP	STD PIP	STD MCP	STD Abduction
12.8°	13.4°	8.9°	9.1°

B. Kapandji Test

The Kapandji test [33] is used to assess the thumb-finger opposition motions (Fig. 13). The opposition movements induce high-range flexion-extension motions of the three phalanges of all the fingers. This classical medical test is used in our experiments to evaluate the measurement accuracy of large joint bending at a low speed for the three devices. Figures 14, 15, and 16 compare the evolution of the reference joint angle in red and each device joint angles in blue.

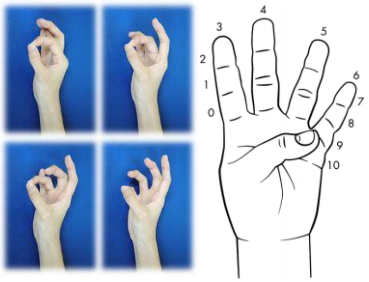

Fig. 13. The Kapandji test : thumb opposition evaluation

1) *The VRFree glove*

The Kapandji test in Fig. 14 shows that the VRFree glove is quite reliable to detect finger high-amplitude flexion-extension motions, even though some parasitic spikes remain.

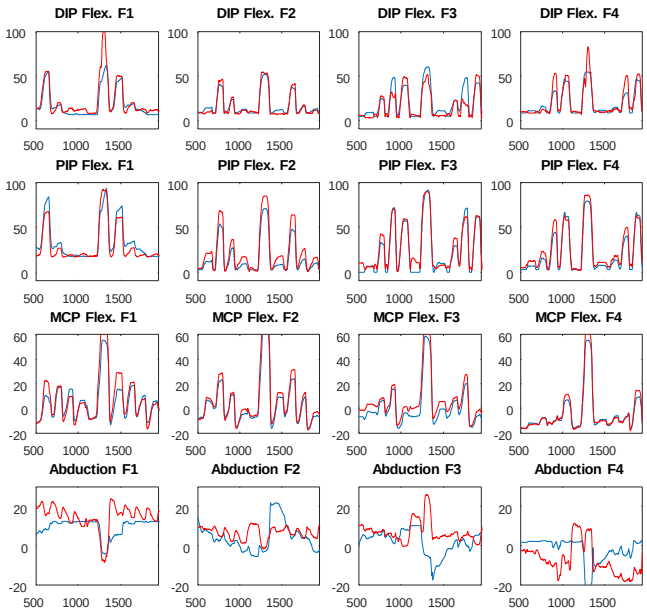

Fig. 14. Joint angles (deg) measured with VRFree (blue) and with the reference system (red) for the Kapandji test

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The measure is quite precise over the total motion range of 100°, according to the mean errors given in Table IV for the four fingers. The measurement of abduction-adduction motions is less precise, because of sensing amplification and filtering of smaller-range motions.

Table IV: STD angles for the fingers motions measured with VRFree

STD DIP	STD PIP	STD MCP	STD Abduction
4.7°	6.2°	5.9°	10.9°

2) *The Manus VR glove*

Fig. 15 shows the joint angles while performing the Kapandji test. These results clearly stress that the small flexion-extension motions of the fingers are not reliably detected. However, the glove is efficient when measuring large finger motions.

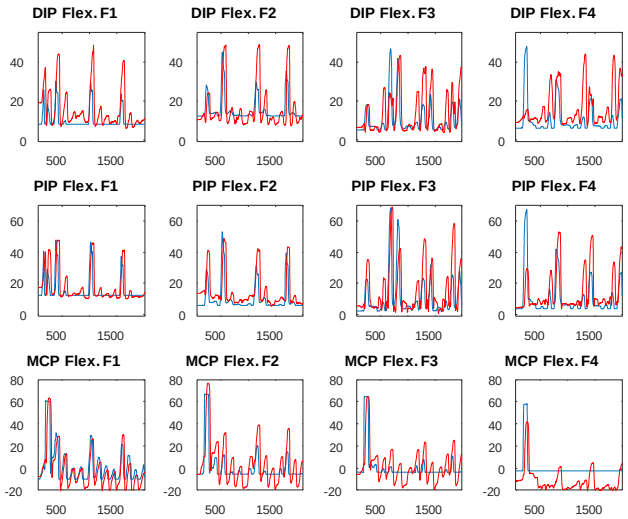

Fig. 15. Joint angles (deg) measured with the Manus VR (blue) and with the reference system (red) for the Kapandji test

The measurements of the abduction-adduction motions are poor or are not even detected.

The STD angles are summarized in Table V. The system is less precise than the other data glove for this kind of motions. The error is mainly due to numerous non-detected small finger flexion motions.

Table V: STD angles for the fingers motions measured with Manus VR

STD DIP	STD PIP	STD MCP
8.5°	9.4°	13.3°

3) *The Leap Motion Controller (LMC)*

Fig. 16 shows that the system is very reliable for the measurements of the MCP flexion-extension motions. But there are many parasitic points on the flexion-extension measurements of the other joints. The measured angles are overestimated, when detected, for these joints' motions. The abduction-adduction motions are often slightly underestimated with the LMC.

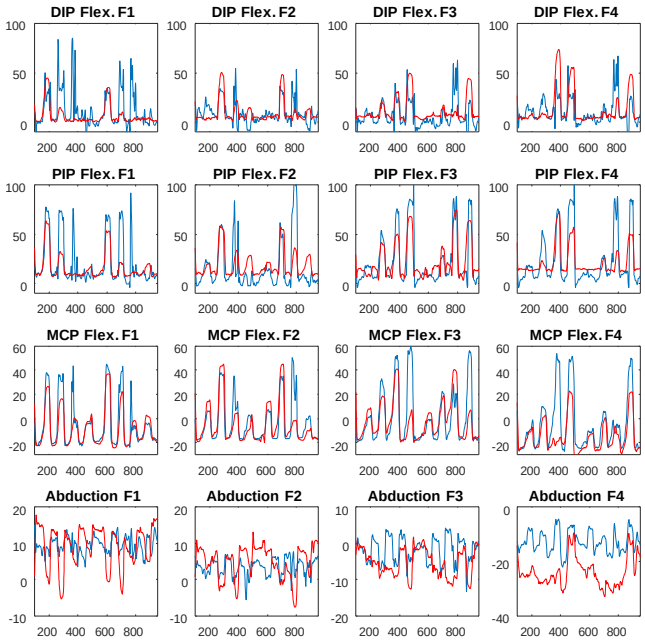

Fig. 16. Joint angles (deg) of the LMC (blue) and with the reference system (red) for the Kapandji test

The STD results, presented in Table VI, demonstrate that this device is the most precise regarding the MCP flexion and the abduction of all the fingers. However, this accuracy decreases when measuring DIP flexion.

Table VI: STD angles for the fingers motions measured with the LMC

STD DIP	STD PIP	STD MCP	STD Abduction
10.2°	6.6°	4.1°	9.4°

D. *Influence of the human hand location*

Some hand-tracking devices need to place the human hand in a specific area relatively to a base frame. To evaluate the influence of the distance between the device base and the user hand on the measurement precision, similar experiments are repeated at three different heights: H1, H2, H3.

1) *The VRFree glove*

The VRFree glove communicates through Bluetooth with its base. For the tests, the hand is placed horizontally above the base at three different heights: H1=20 cm, H2=40 cm, H3=60 cm.

As highlighted on Table VII and Fig. 17, there is no significant influence of the height on the device precision.

Table VII: STD angles for three heights measurements with the VRFree

	DIP	PIP	MCP	ABD
H=20cm	11.5°	8.4°	7.4°	10°
H=40cm	11.2°	7.8°	6.9°	10.1°
H=60cm	8.6°	6.6°	5.9°	12.4°

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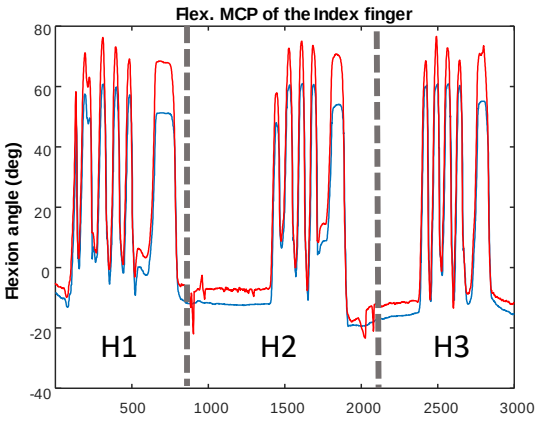

Fig. 17. Influence of the height on the VRFree precision

2) The Manus VR glove

The Manus VR glove does not use any reference base to track the user hand, and therefore, the user can perform the motions anywhere in space.

3) The Leap Motion Controller (LMC)

The measures of the LMC are based on a grounded camera. We evaluated the influence of the distance between the user's hand and the camera, varying from H1=30 cm, H2=50 cm, to H3=75 cm. The results on Fig. 18 and Table VIII underline that the distance highly impacts the measurement quality. As the distance to the camera increases, the results become very imprecise, especially for the PIP and DIP flexion-extension motions.

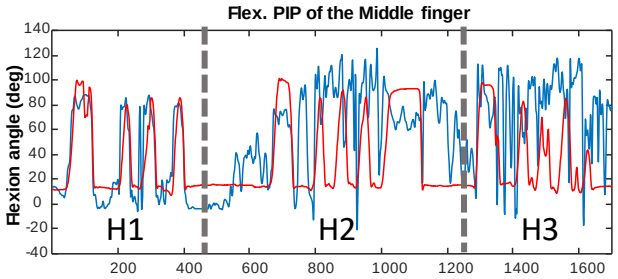

Fig. 18. Influence of the height on the LMC precision

Table VIII: STD angles for three heights measurements with the LMC

	DIP	PIP	MCP	ABD
H=30cm	14.3°	19.1°	9.5°	11.3°
H=50cm	23.4°	18.8°	12.9°	10.0°
H=75cm	31.4°	26.2°	25.2°	14.1°

E. Influence of the hand orientation

To evaluate the influence of the hand orientation θ_h on the measurement accuracy, similar gestures are captured at three different orientations: horizontal hand and palm down (θ_h =0°), vertical hand (θ_h =90°) and horizontal hand palm up (θ_h =180°).

1) The VRFree Glove

The VRFree glove is calibrated in the horizontal position before each test. The orientation of the wrist is given by IMU. As we can see in Fig. 19, there is a significant influence of the hand orientation on the measurement precision. As the measure quality is similar for flexion motions of all the fingers, we chose to illustrate the influence of the hand orientation with the index finger's DIP flexion. The system gives good results in the first configuration (θ_h =0°), the results are mitigated in the second configuration (θ_h =90°), and very bad at θ_h =180°.

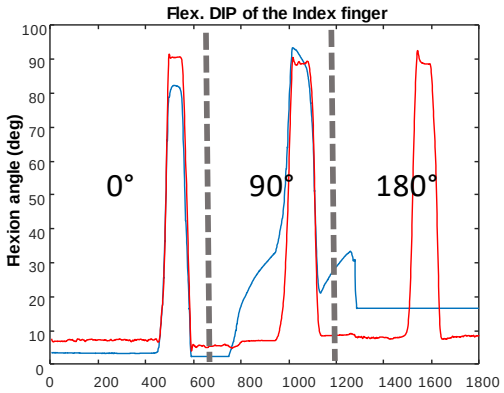

Fig. 19. Influence of the orientation on the VRFree precision

The standard deviation angles (STD) are calculated for the three configurations of the hand (see Table IX) and confirm the conclusions. The accuracy drop can be explained as the glove slips on the user skin while rotating their hand, which affects the IMU and bending sensors' observations.

Table IX: STD angles for three orientations measurements with the VRFree

	DIP	PIP	MCP	ABD
θ_h =0°	8.3°	7.2°	6.6°	12.7°
θ_h =90°	19°	19.7°	21.4°	19.6°
θ_h =180°	32.5°	40.7°	NA	NA

2) The Manus VR glove

Here again, the wrist orientation is calculated thanks to the glove's IMU, calibrated before each test.

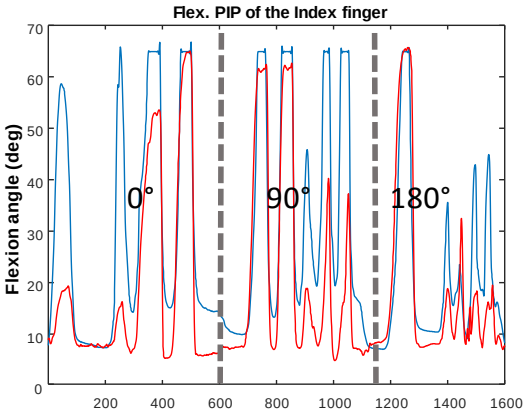

Fig. 20. Influence of the orientation on the Manus VR precision

Fig. 20 and Table X underline no significant influence of the hand orientation on the results. The glove gives slightly better

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results when the hand is placed horizontally, whatever the direction of the palm. This example stresses once again the tendency of the glove to overestimate low amplitude flexions.

Table X: STD angles for three orientations measurements with Manus VR

	DIP	PIP	MCP
θ_h =0°	6.8°	12.1°	8.1°
θ_h =90°	8.1°	12.4°	7.5°
θ_h =180°	4.9°	7.2°	5.3°

3) *The Leap Motion Controller (LMC)*

As illustrated by Fig. 21 and Table XI, the hand orientation highly influences the flexion accuracy. The results are quite good within the horizontal plane, but the system suffers from important errors when the hand is maintained vertically. These errors can originate from occlusions occurring when the hand is perpendicular to the camera in the LMC frame.

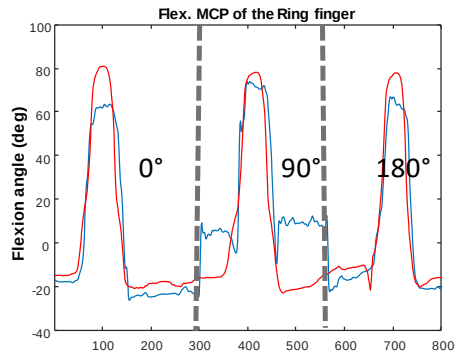

Fig. 21. Influence of the orientation on the LMC precision

Table XI: STD angles for three orientations measurements with the LMC

	DIP	PIP	MCP	ABD
θ_h =0°	7.3°	8.2°	6.3°	8.0°
θ_h =90°	12.7°	11.9°	18.6°	12.1°
θ_h =180°	8.4°	5.1°	5.7°	7.1°

V. EVALUATION OF THE FINGERTIP POSITION ACCURACY

A. *Positions of the fingertips*

When performing teleoperated or virtual fine manipulation tasks, the precise knowledge of the fingertip positions is necessary. We evaluated the accuracy of the fingertip position measurement while performing the Kapandji test motion. The average positioning error, with respect to the motion capture fingertip reference position, is computed for the three hand-tracking devices. As the two data gloves only provide joint data, the fingertip positions are calculated from the gloves' rotation matrix and the geometric parameters of the user's hand. The direct geometrical model of the kinematic chains drawn on Fig. 22 give the relation between the joint and fingertip positions.

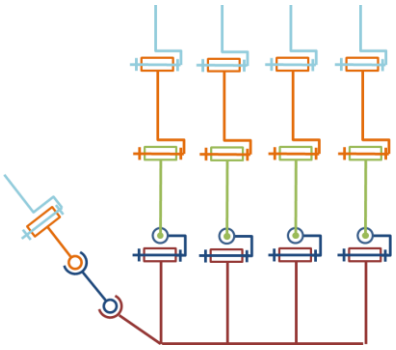

Fig. 22. Kinematic diagram of the hand

The rotation matrix for the i^{th}joint of the finger is noted:

$$R_i = R(\theta x_i).R(\theta y_i).R(\theta z_i) \quad (2)$$

where $\theta x_i, \theta y_i, \theta z_i$ are the rotation angles around the axes x, y and z respectively. The vector $q_i = [\theta x_i, \theta y_i, \theta z_i]^T$ defines these rotational coordinates.

The position vector P_i of the i^{th} joint is given by the function:

$$g(q_i) = P_i = P_{i-1} + R_i.\begin{bmatrix}0\\0\\L_i\end{bmatrix} \quad (3)$$

where L_i is the length of i^{th} phalanx. P_0 is the position vector that describes the attachment of the finger on the palm.

1) *The VRFree Glove*

As the VRFree glove only provides joint data, we reconstruct the fingertip positions based on the method presented above. If a different operator uses the device, the user-dependent geometric parameters (finger placement, phalange length) have to be updated to get correct positions. The hand dimensions were measured with a simple ruler to be close to the common use of the glove. The dimensions of the subject's phalanges are displayed in Table XII, and compared with the motion capture estimates noted in red.

Table XII: Geometric dimensions of the hand for the VRFree Glove. (black values based on the model computation vs red values based on motion capture)

	Index	Middle	Ring	Little	Thumb
Proximal phalanx	50 mm *48 mm*	52 mm *56 mm*	47 mm *50 mm*	44 mm *41 mm*	38 mm *38 mm*
Intermediate phalanx	32 mm *29 mm*	35 mm *35 mm*	30 mm *32 mm*	24 mm *25 mm*	36 mm *40 mm*
Distal phalanx	24 mm *26 mm*	24 mm *26 mm*	24 mm *26 mm*	22 mm *24 mm*	26 mm *27 mm*

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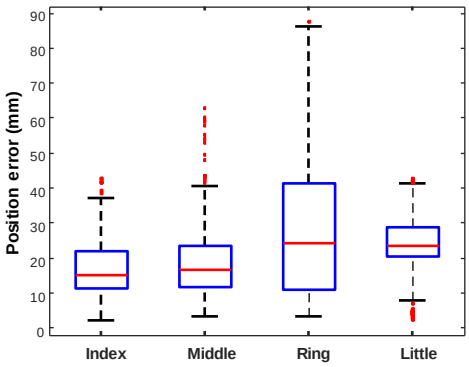

Fig. 23. Position of the fingertips measured with the VRFree glove

Fig. 23 shows the calculated standard deviation for the different fingertips. On each box, the central red mark indicates the median, and the bottom and top edges of the box indicate respectively the 25th and 75th percentiles. The bars extend to the end values. Observed outliers are plotted individually in red. The mean positioning error for all the fingers is 21.8 mm. The error increases along the x-axis (see Fig. 9). This phenomenon can come from the imprecision in the abduction-adduction measurements. Besides, the results are decent, as long as the kinematic model of the user's hand is good enough.

2) The Manus VR glove

Manus VR includes their own hand model in the software with the phalangeal setting summarized in Table XIII. These geometric parameters match the average dimension of a human hand and are quite close to those of our subject medium-size hand. The calibration process only adjusts an angular offset for the joint angular measurements and not the fingers' size or location on the palm.

Table XIII: Geometric dimensions of the hand for the Manus VR Glove. (black values based on the model computation vs red values based on motion capture)

	Index	**Middle**	**Ring**	**Little**	**Thumb**
Proximal phalange	51 mm *48 mm*	55 mm *56 mm*	50 mm *50 mm*	40 mm *41 mm*	47 mm *38 mm*
Intermediate phalange	27 mm *29 mm*	31 mm *35 mm*	28 mm *32 mm*	20 mm *25 mm*	40 mm *40 mm*
Distal phalange	22 mm *26 mm*	25 mm *26 mm*	25 mm *26 mm*	23 mm *24 mm*	31 mm *27 mm*

The Manus VR SDK provides the fingertip positions directly calculated with its geometric model. Even though the user hand size was close from their model, the computed fingertip measures present a poor accuracy (Fig. 24). The mean positioning error for the four fingers is 39.8 mm. This large error is due to inaccuracies in the geometric model, and particularly because the glove does not consider the abduction of the fingers.

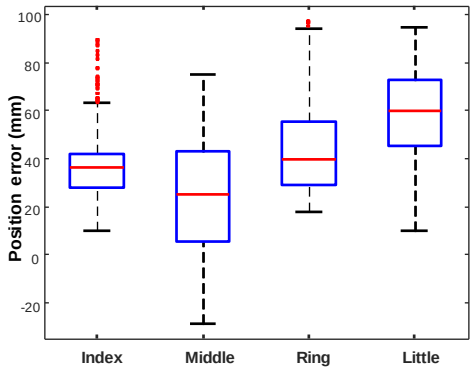

Fig. 24. Position of the fingertips measured with the Manus VR

3) The Leap Motion Controller (LMC)

Unlike the data gloves, the LMC directly provides the position and orientation of each phalanx in Cartesian space. The LMC automatically adapts to a new user by recalculating the geometric model of their hand.

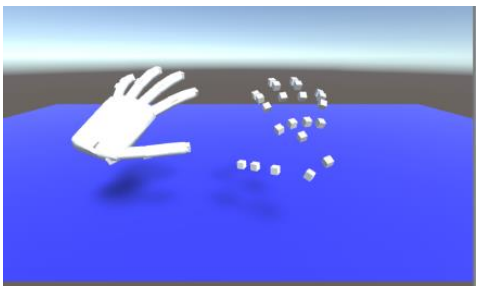

Fig. 25. The displacements of each phalanx given by the LMC SDK. Position and orientation are represented by the cubes for the right-hand

Table XIV: Geometric dimensions of the hand for the LMC. (black values based on the model computation vs red values based on motion capture)

	Index	**Middle**	**Ring**	**Little**	**Thumb**
Proximal phalange	39 mm *48 mm*	43 mm *56 mm*	40 mm *50 mm*	32 mm *41 mm*	47 mm *38 mm*
Intermediate phalange	22 mm *29 mm*	26 mm *35 mm*	25 mm *32 mm*	17 mm *25 mm*	41 mm *40 mm*
Distal phalange	12 mm *26 mm*	13 mm *26 mm*	13 mm *26 mm*	12 mm *24 mm*	16 mm *27 mm*

The average positioning errors for the four fingers with the LMC are presented on Fig. 26. The average lengths of the phalanges provided by the LMC are summarized in Table XIV and compared with the motion-capture-based reference values. The average positioning error is 27.4 mm. We mainly observe errors along the z-axis (see Fig. 9) which can be explained because in the hand horizontal configuration the motions occurring in the plane (x,y), perpendicular to the camera, are not properly detected. Along the other axes, the LMC is accurate.

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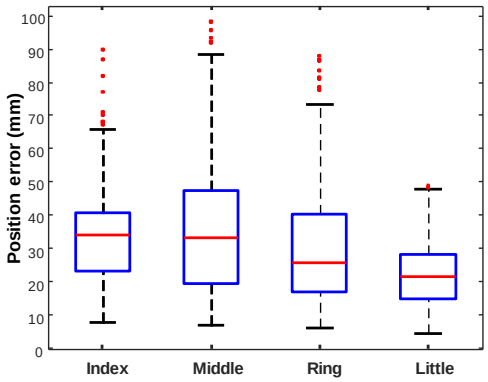

Fig. 26. Position of the fingertips measured with the LMC

B. *Focus on the reconstruction of the thumb fingertip position*

The kinematic model of the human thumb is complex [34], as the motions of the first two joints are interrelated, and because the centers of rotation are difficult to localize. Consequently, the thumb flexion angles calculated through the motion capture data are not precise. Moreover, as the first joint of the thumb is equivalent to a spherical joint, the sequential comparison of each flexion angle between all the devices seems unfair. Therefore, the comparison will only focus on the thumb fingertip position. Accurately estimate the thumb fingertip position is a major concern as it plays a key role in every grasp or inside-hand manipulation, by acting in opposition to the other fingers. The rotation matrices of the frames attached to each thumb phalange, provided by the data gloves, are uncertain and depend on the shape of the user hand. It is necessary to transform the angles given by the data glove to express the fingertip position in the base frame of the motion capture system. The angular shifts to be applied to the glove measures of the thumb joint angles are calculated with the least square method in order to improve the mapping between the motion capture reference thumb tip and the device measurement. The angular shift of the i^{th} joint of the thumb is $dq_i = [d\theta x_i, d\theta y_i, d\theta z_i]$, and the reference position of the i^{th}joint of the thumb provided by the motion capture system is $Pref_i$. We choose the angular shift dq_i that minimizes the following function:

$$f(x) = \sqrt{(\sum_{i=1}^{3}(g(q_i + dq_i) - Pref_i)^2)} \qquad (4)$$

where g is the function that gives the joint position from (3).

The thumb fingertip measurement precision is analyzed while performing the Kapandji test. The Kapandji motion covers the entire thumb workspace which makes it a good test to observe the full range of measurements for the different devices. These shift coefficients depend on the user hand, and on the chosen calibration motion. This calibration method requires precise reference values as the ones obtained by motion capture.

1) *The VRFree glove*

With the calculated shift coefficients, the mean error on the thumb position is 22.7 mm, which is consequent. The error can be caused by inaccuracies of the IMU angular measurements at the first two thumb joints as the sensor is sliding on the user hand. Fig. 27 represents the thumb fingertip positions during the Kapandji test. The hand initial position appears in blue, the motion-captured thumb position is plotted in red and the thumb position calculated from the VRFree data in green.

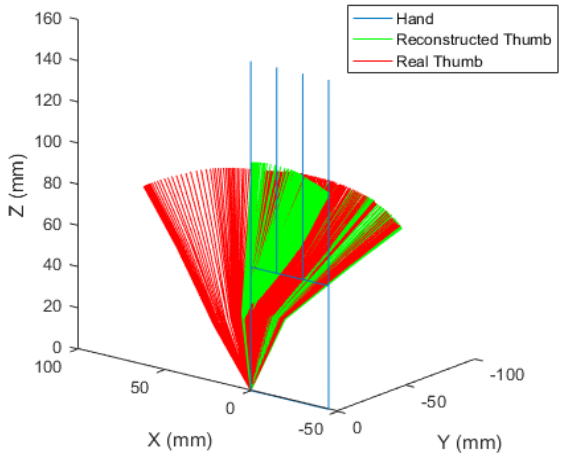

Fig. 27. Position of the thumb for the Kapandji test with the VRFree glove

The glove stays quite reliable when measuring the thumb flexion-extension motions but is not able to measure the whole range of abduction-adduction motions.

2) *The Manus VR glove*

The angular shift coefficients are computed to transform the Manus VR data into the appropriate frame. After this calibration, the mean error on thumb tip position is 16.2 mm. The results on the thumb fingertip are close to the reference. Fig. 28 show the different thumb positions, measured by the motion capture system in red, and rebuilt from the device data in green, while performing the Kapandji test. The Manus VR glove fails to measure the whole range of motion of the thumb. It cannot detect the full thumb extension. It is worth noting that the thumb orientation is computed by an IMU which requires to repeat a long calibration process before each measurement, as the measures drifted very quickly.

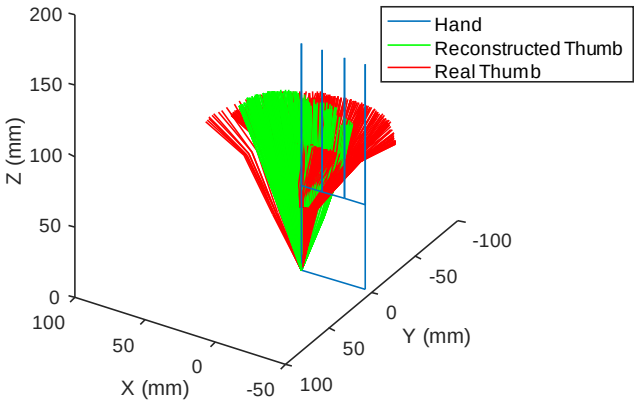

Fig. 28. Position of the thumb for the Kapandji test with the Manus VR glove

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3) *The Leap Motion Controller (LMC)*

The LMC directly provides the positions of the thumb joints. The mean error on the thumb tip position is 9.6 mm. Fig. 29 presents the different thumb positions, measured by the motion capture system in red, and given by the LMC in green, while performing the Kapandji test. Apart from maximal thumb flexion motions, the position of the thumb fingertip is accurately captured by the LMC.

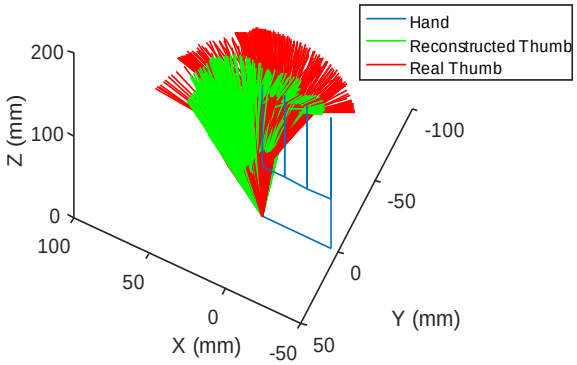

Fig. 29. Position of the thumb for the Kapandji test with the LMC

C. *Evaluation of the distance between the thumb and the other fingers*

Controlling the distance between the thumb and opposable fingers is essential to ensure adequate pre-grasp configurations and secure stable and precise grasps. While performing dexterous manipulation tasks, a closed kinematic chain between two fingers (generally with the thumb) is controlled with respect to the object contact points. We evaluated the average error on the distance between the thumb and the other fingers during the Kapandji test. As the fingers come into contact, the distance should become zero. We only consider the fingertip contact phase, to avoid bias due to the flexion-extension motions.

1) *The VRFree Glove*

The average distances between the thumb and each fingertip are displayed during the contact phase of the Kapandji test on Fig. 30. The solid lines represent the thumb-finger distances measured with the motion capture system. Given the position of the markers on the hand fingertips (see Fig. 8), and as the contact naturally occurs on the finger pulp, the measured contact distance is never exactly 0. The dotted lines detail the distance captured with the VRFree glove.

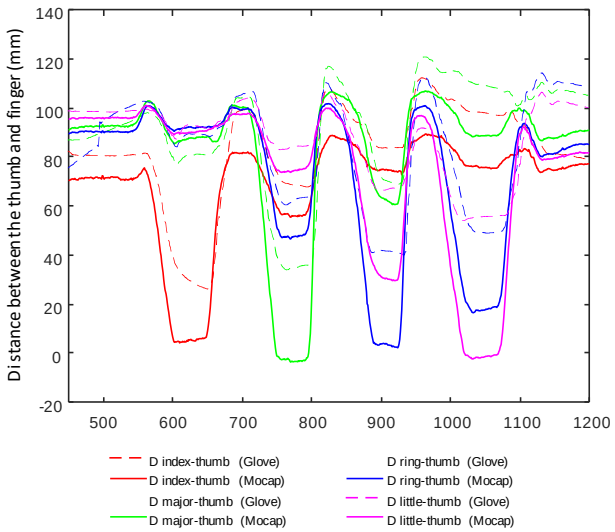

Fig. 30. Distance between thumb and other fingers for VRFree glove

The distances between the thumb and other fingers follow a similar behavior for the four finger-thumb contacts. This could be explained by the fact that the glove does not perceive properly the thumb abductions. This limitation particularly induces an overestimation of the thumb-pinky distance. The average distance between the thumb and other fingers during the contact phases is 37.3 mm (Table XV). This value is far from the real value which should be around zero.

Table XV: Thumb-finger distance error during contact for VRFree glove

Finger	Index	Middle	Ring	Little
Mean error during the contact phase	23.2 mm	33.7 mm	37.2 mm	55.3 mm

2) *The Manus VR Glove*

Here again, the errors in the closed kinematic chain are relatively important, as it can be seen on Fig. 31. These errors originate from the absence of abduction-adduction measurement and from the inaccuracies on the thumb position.

Table XVI shows that the average thumb-finger distance error is 33 mm during the contact phases.

Table XVI: Thumb-finger distance error during contact for Manus VR glove

Finger	Index	Middle	Ring	Little
Mean error during the contact phase	16.4 mm	32.3 mm	24.6 mm	58.9 mm

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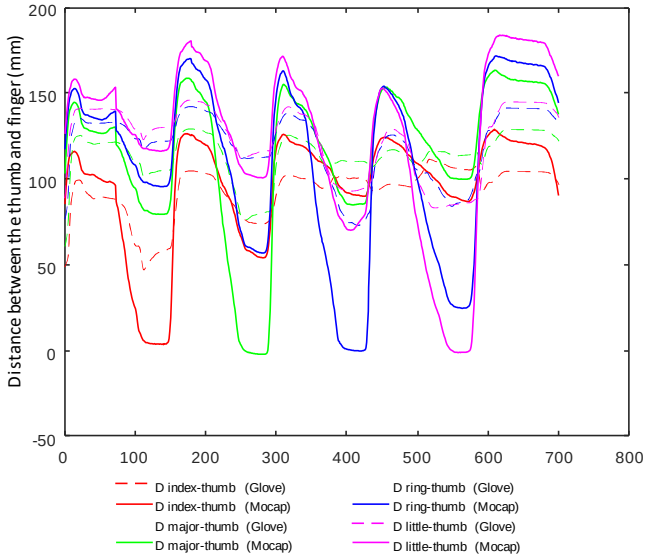

Fig. 31: Distance between thumb and other fingers for the Manus VR glove

3) The Leap Motion Controller (LMC)

The distances between every thumb and finger tips, provided by the LMC and the motion capture system, are presented on Fig. 32 during the Kapandji test.

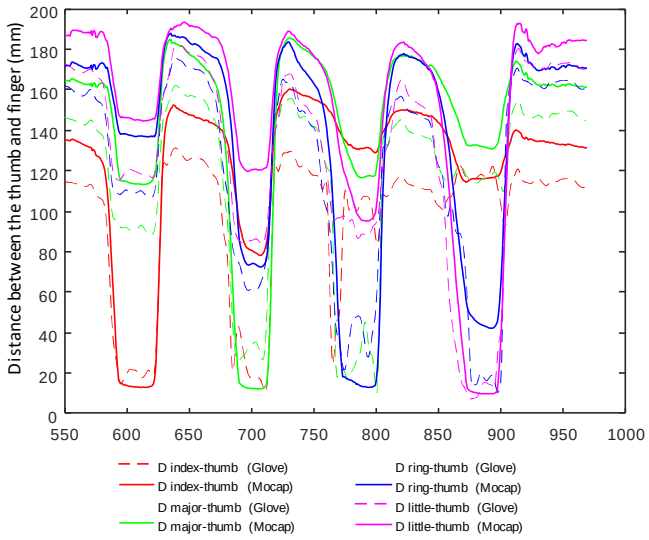

Fig. 32: Distance error between thumb and other fingers for the LMC

The distance errors are less important than the results obtained with the two data gloves. Indeed, the LMC can automatically calibrate the morphology of the user hand and capture the thumb motions more accurately.

The average thumb-finger distance error during contact is 8 mm (Table XVII). This result underlines a significant improvement compared to the VRFree and Manus VR gloves.

Table XVII : Thumb-finger distance error during contact for the LMC

Finger	Index	Middle	Ring	Little
Mean error during the contact phase	6.3 mm	12.4 mm	9.2 mm	4.7 mm

VI. Discussion – Results analysis

The different experimental tests made it possible to evaluate the performances of the three devices. The results are summarized and analyzed below. Seven experimentations have been carried out with each device: 1) random gestures of the fingers, 2) Kapandji test, 3) motion of the thumb, 4) influence of the hand location, 5) influence of the hand orientation, 6) fingertip positions, 7) distance between thumb and other fingers.

These experimental results rise to conclusions on the performances and measurement accuracy that can be expected for each device. The VRFree glove is quite reliable for the evaluation of finger flexion-extension motions. However, abduction-adduction motions and the thumb orientation are poorly measured. The VRFree data depend on the IMU situated at the hand base, near the wrist. Slippages occurring between the IMU and the wrist lead to errors and impact the glove accuracy. A Velcro strap is used to tighten the glove at the wrist and limit this slippage, but this fixture may not be robust enough. Moreover, the glove only works properly within a horizontal plane as demonstrated with the hand orientation test. The VRFree glove is comfortable and has a convenient battery life about 45 min. The IMU needs to be calibrated before each use but the procedure is very fast as the user only needs to place their hand at certain positions. The glove only exists in three sizes and may not perfectly suit every user, resulting in measurement errors due to displacements of the sensors on the hand. The Manus VR glove presents poorer performances than the VRFree glove but is robust to changes in the hand orientation. The glove fabric fits more tightly than the VRFree, thanks to a better-quality textile, which can limit the slippage on the hand skin. Unlike the VRFree, the Manus VR cannot be used during the recharging process. The glove only needs to be calibrated once thanks to the provided SDK through a multi-step procedure. This calibration can be recorded for each user. Nonetheless, due to the IMU drift, the initialization process has to be done before each use. The LMC system is quite precise if the hand is placed in an optimal configuration, within a reduced area (horizontally placed right above the camera). However, the sensors detect many non-existent flexion-extension motions which should be filtered in remote operation of a robotic hand. The device is automatically calibrated to suit the morphology of the user hand. The system is ergonomic and convenient as it adapts to any user and does not interfere with the hand movement at all.

The results for the three devices are summarized in Table XVIII. Green color highlights the best results. The average error is evaluated in the optimal configuration, with the hand placed horizontally and close to the sensor.

Table XVIII: Synthesis of the experimental tests

Device	VRFree Glove	Manus VR Glove	Leap Motion Controller
Average finger bending error	**7.5°**	9.4°	16.5°
Average finger abduction error	13.2°	NA	**7.9°**
Average thumb position error	22.7 mm	16.2 mm	**9.6 mm**

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Average fingertip position error	**21.8 mm**	39.8 mm	27.4 mm
Average finger-thumb distance error	37.3 mm	33 mm	**8 mm**
Robustness to the distance from the sensor	+ +	+ +	-
Robustness to the hand orientation	- -	-	-
Ergonomic comfort	+	-	+ +

VII. Conclusion

This paper has compared the performances of three hand-tracking devices through a comprehensive experimental study. Overall, the data gloves provide a most accurate tracking of flexion-extension angles for the ring, index, middle and little fingers than the LMC. However, the Manus VR is not performant when estimating the fingertip positions, because of an accumulation of measurement errors. The VRFree glove is proven quite precise when used in the optimal horizontal configuration. These better results come partly from the measure of the hand geometric parameters before the test, given an accurate geometric modelling for the computation. The accuracy decreases within other hand orientations as the IMU can slip on the skin. The Manus VR is more robust to changes in configurations, but it lacks precision, particularly for the estimation of the thumb position. This poor reliability makes it unsuitable for remote dexterous manipulation tasks. It can be used to recognize simple and common gestures. The LMC is less precise when measuring finger bending, and strongly depends on the user hand configuration. Otherwise, it provides accurate estimates of the fingertip positions, because its technology aims at tracking the phalanges. Among the three devices, it is the only providing a reliable measurement of the thumb in its whole workspace. Therefore, the LMC is the best device to control a closed kinematic chain between the thumb and an opposite finger, such as in fine manipulation tasks.

This system review gives determinant elements about the relevance of common hand-tracking devices and steers their use in remote robotic or virtual manipulation. When the teleoperation consists in a simple joint to joint tracking, a data glove could be suitable. It would nevertheless require some enhancement to be performant with every hand orientation. But most applications of remote manipulation require accurate measurements of the relative positions between fingertips. The vision-based devices have a significant advantage for this fine teleoperation purpose. Without any tedious calibration process, vision-based systems directly evaluate the user hand's morphology and adjust the hand modelling to accurately compute the fingertip positions.

The study and rating of these different hand-tracking devices provide a strong foundation to select proper technologic solutions in any remote application. In the SeaHand project [1], a motion capture system is chosen to track the archeologist' hand in order to teleoperate the robotic hand embedded on ROV from the boat. This motion capture system is the only solution able to provide the required precision, in any hand configurations, to perform robust and safe grasps of fragile objects undersea. This system does not interfere with the user motions letting them focus on their delicate grasping task. The motion capture system could be associated with a second redundant simpler system, such as a data glove, in order to secure the human hand tracking.

References

[1] http://anr-seahand.prd.fr/ : web site of the SEAHAND ANR (French National Research Agency) funded project.

[2] Guna, Jože, et al. "An analysis of the precision and reliability of the leap motion sensor and its suitability for static and dynamic tracking." Sensors 14.2 (2014): 3702-3720.

[3] Jakus, Grega, et al. "Evaluation of leap motion controller with a high precision optical tracking system." International Conference on Human-Computer Interaction. Springer, Cham, 2014.

[4] Weichert, Frank, et al. "Analysis of the accuracy and robustness of the leap motion controller." Sensors 13.5 (2013): 6380-6393.

[5] Sturman, M.M.; Vaillancourt, D.E.; Corcos, D. Effects of aging on the regularity of physiological tremor. J. Neurophysiol. 2005, 93, 3064–3074.

[6] Smeragliuolo, Anna H., et al. "Validation of the Leap Motion Controller using markered motion capture technology." Journal of biomechanics 49.9 (2016): 1742-1750.

[7] Rautaray S., Agrawal A. Vision based hand gesture recognition for human computer interaction: A survey. Artif. Intell. Rev. 2015;43:1–54. doi: 10.1007/s10462-012-9356-9.

[8] Erol A., Bebis G., Nicolescu M., Boyle R.D., Twombly X. Vision-based hand pose estimation: A review. Comput. Vis. Image Underst. 2007;108:52–73. doi: 10.1016/j.cviu.2006.10.012.

[9] A. Tkach, A. Tagliasacchi, E. Remelli, M. Pauly, and A. Fitzgibbon, "Online generative model personalization for hand tracking," ACM Trans. Graph., vol. 36, no. 6, pp. 1–11, 2017.

[10] P. D. S. H. Gunawardane and N. T. Medagedara, "Comparison of hand gesture inputs of leap motion controller & data glove into a soft finger," Proc. - 2017 IEEE 5th Int. Symp. Robot. Intell. Sensors, IRIS 2017, vol. 2018–January, pp. 62–68, 2018.

[11] L. Dipietro, A. M. Sabatini, S. Member, and P. Dario, "A Survey of Glove-Based Systems and Their Applications," vol. 38, no. 4, pp. 461–482, 2008.

[12] Machida, Kazuo, et al. "Precise space telerobotic system using 3-finger multisensory hand." Robotics and Automation, 1995. Proceedings, 1995 IEEE International Conference on. Vol. 1. IEEE, 1995.

[13] Stuart, Hannah, et al. "The ocean one hands: An adaptive design for robust marine manipulation." *The International Journal of Robotics Research* 36.2 (2017): 150-166.

[14] Bassily, D., et al. "Intuitive and adaptive robotic arm manipulation using the leap motion controller." ISR/robotik 2014; 41st international symposium on robotics; proceedings of. VDE, 2014.

[15] Peppoloni, Lorenzo, et al. "Immersive ros-integrated framework for robot teleoperation." 3D User Interfaces (3 DUI), 2015 IEEE Symposium on. IEEE, 2015.

[16] Heisnam, Lamyanba, and Bhivraj Suthar. "20 DOF robotic hand for tele-operation:—Design, simulation, control and accuracy test with leap motion." Robotics and Automation for Humanitarian Applications RAHA), 2016 International Conference on. IEEE, 2016.

[17] Leeper, Adam Eric, et al. "Strategies for human-in-the-loop robotic grasping." Proceedings of the seventh annual ACM/IEEE international conference on Human-Robot Interaction. ACM, 2012.

[18] Bitzer, Sebastian, and Patrick Van Der Smagt. "Learning EMG control of a robotic hand: towards active prostheses." Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on. IEEE, 2006.

[19] Farry, Kristin A., Ian D. Walker, and Richard G. Baraniuk. "Myoelectric teleoperation of a complex robotic hand." IEEE Transactions on Robotics and Automation 12.5 (1996): 775-788.

[20] Vogel, Jörn, Claudio Castellini, and Patrick van der Smagt. "EMG-based teleoperation and manipulation with the DLR LWR-III." Intelligent

Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on. IEEE, 2011.

[21] Artemiadis, Panagiotis K., and Kostas J. Kyriakopoulos. "EMG-based teleoperation of a robot arm in planar catching movements using ARMAX model and trajectory monitoring techniques." Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on. IEEE, 2006.

[22] Diftler, Myron A., et al. "Evolution of the NASA/DARPA robonaut control system." Robotics and Automation, 2003. Proceedings. ICRA'03. IEEE International Conference on. Vol. 2. IEEE, 2003.

[23] Jau, Bruno M. "Dexterous telemanipulation with four fingered hand system." Robotics and Automation, 1995. Proceedings., 1995 IEEE International Conference on. Vol. 1. IEEE, 1995.

[24] Fischer, Max, Patrick van der Smagt, and Gerd Hirzinger. "Learning techniques in a data glove based telemanipulation system for the DLR hand." Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on. Vol. 2. IEEE, 1998.

[25] Rohling, Robert N., John M. Hollerbach, and Stephen C. Jacobsen. "Optimized fingertip mapping: a general algorithm for robotic hand teleoperation." Presence: Teleoperators & Virtual Environments 2.3 (1993): 203-220.

[26] Kobayashi, Futoshi, et al. "Two-fingered haptic device for robot hand teleoperation." Journal of Robotics 2011 (2011).

[27] Ali, Michael S., and Charles Engler Jr. "System description document for the Anthrobot-2: a dexterous robot hand." (1991).

[28] Hashimoto, Hideaki, et al. "An unilateral master-slave hand system with a force-controlled slave hand." Robotics and Automation, 1995. Proceedings., 1995 IEEE International Conference on. Vol. 1. IEEE, 1995.

[29] Cutkosky, Mark R. "On grasp choice, grasp models, and the design of hands for manufacturing tasks." *IEEE Transactions on robotics and automation* 5.3 (1989): 269-279.

[30] F. Gonzalez, F. Gosselin et W. Bachta, 'Analysis of hand contact areas and interaction capabilities during manipulation and exploration', IEEE Transactions on Haptics, Vol. 7, No. 4, Oct.-Dec. 2014, pp. 415-429.

[31] F. Gonzalez, F. Gosselin et W. Bachta, 'A framework for the classification of dexterous haptic interfaces based on the identification of the most frequently used hand contact areas', Proc. IEEE World Haptics Conference, Daejeon, Korea, April 2013, pp. 461-466.

[32] Rash, G. S., Belliappa, P. P., Wachowiak, M. P., Somia, N. N., & Gupta, A. (1999). A demonstration of the validity of a 3-D video motion analysis method for measuring finger flexion and extension. Journal of Biomechanics, 32(12), 1337-1341.

[33] Kapandji A (1986). "Clinical test of apposition and counter-apposition of the thumb". Ann Chir Main. 5 (1): 67–73

[34] Katarincic, Julie A. "Thumb kinematics and their relevance to function." *Hand clinics* 17.2 (2001): 169-174.

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