Subjective perceptions when using motion tracking systems – a comparison among healthy subjects, individuals post-stroke, and therapists

R Lloréns[1,2], A Borrego[1], E Parra[1], V Naranjo[1], E Noé[2], M Alcañiz[1,3]

[1]Instituto Interuniversitario de Investigación en Bioingeniería y Tecnología Orientada al Ser Humano,
Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, SPAIN

[2]Servicio de Neurorrehabilitación de los Hospitales NISA Valencia al Mar y Sevilla
Aljarafe, Fundación Hospitales NISA, Valencia, SPAIN

[3]Ciber, Fisiopatología Obesidad y Nutrición, CB06/03 Instituto de Salud Carlos III, Av. Sos Baynat s/n,
Univesity of Jaume I, 12071 Castellón, SPAIN

rllorens@labhuman.com

[1]*www.labhuman.com*, [2]*www.neurorhb.com*

ABSTRACT

Different tracking technologies allow users to interact with virtual reality environments. Most research regarding tracking systems has focused on studying their performance parameters, mainly accuracy. However, even though subjective parameters also determine the responses evoked by the virtual reality experience, least efforts have been made to study their influence. The subjective perceptions of healthy subjects, individuals post-stroke, and physical therapists after using three tracking technologies (optical, electromagnetic, and skeleton tracking) to interact with a virtual rehabilitation exercise were collected via questionnaire. Results showed that subjective perceptions and preferences are far from being constant among different populations, thus suggesting that these considerations, together with the performance parameters, should be taken into account when designing a rehabilitation system.

1. INTRODUCTION

Virtual Reality (VR) can recreate synthetic environments that can be tailored to provide specific sensory stimulation in different channels. However to immerse individuals in an alternative reality, not only the stimulation is required, but also the virtual environment (VE) must react in a similar way as the real world, at least in certain aspects (Bangay et al, 1998). Interaction with the VEs has been a technical challenge through the years. In order to detect and transfer the users' movements to the VE, different tracking solutions have been proposed. Tracking systems estimate the location and orientation of known targets with six degrees of freedom and transfer the data to the virtual world in real time (Burdea et al, 2003). Traditionally, three main physical principles have been used to locate the targets, therefore classifying the tracking systems as either optical, electromagnetic, or inertial (or hybrid solutions combining the mentioned mechanisms).

Recent advances in technology have given rise to cheaper motion tracking solutions based on depth sensors, as the Microsoft® Kinect™ (Microsoft®, Washington) or the ASUS® Xtion Pro (ASUS®, Taipei), both equipped with the PS1080 chipset (PrimeSense™ Ltd, Tel Aviv). According to the previous classification, these solutions can be considered as optical-based, because they estimate the depth information of a scene, but they are complemented with a statistical method to estimate the main joints of the human silhouettes present on the captured scene (Shotton et al, 2011). Even though the classical definition of tracking systems requires the location of a target with six degrees of freedom, the location of the joints provided by the skeleton tracking is enough to interact with a great number of VE. The low cost of these devices, their comfort (no wearable sensors are needed), and their off-the-self availability have facilitated their widespread use (Llorens et al, 2012).

All the tracking technologies present different characteristics that are inherent to the physical principle in which they are based on. Consequently, a tracking system can be defined by some parameters, such as accuracy, jitter, drift, and latency (Burdea et al, 2003). Several studies have compared the performance of different tracking solutions according to these parameters (Mobini et al.; Khoshelham et al, 2012; Clark et al, 2013). However, even though subjective considerations determine the VR experience, thus modulating the immersion and presence of the users (Weiss et al, 2006), limited research has focused on these aspects when using tracking

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systems. Interestingly, people with neurological impairments, as individuals post-stroke, who are one of the targets of the VR-based rehabilitation systems, may present sensory, motor, cognitive, and emotional impairments that can affect their interaction with the world (Kauhanen et al, 2000; Suenkeler et al, 2002), and consequently, their subjective perceptions when using tracking system.

The objective of this study was to evaluate the subjective perceptions elicited when using three different tracking technologies, optical, electromagnetic and skeleton tracking, in three different populations: healthy subjects, individuals post-stroke, and physical therapists.

2. METHODS

2.1 Participants

Three different groups of participants were recruited. The age of healthy subjects and individuals post-stroke was matched.

- *Healthy individuals.* The inclusion criteria in the healthy group were 1) age ≥ 55 and < 80; and 2) absence of previously reported motor or cognitive limitations. Individuals with previous experience with VR-based systems were excluded.

- *Subjects post-stroke.* The inclusion criteria in the stroke group were 1) age ≥ 55 years old and < 80 years old; 2) chronicity > 6 months; 3) absence of severe cognitive impairment as defined by Mini-mental state examination (Folstein et al, 1975) cut-off > 23; 4) able to follow instructions; 5) ability to maintain stride-standing position for 30 s without holding onto or assistance from another person as specified in the Brunel balance assessment, section 3, level 7 (Tyson et al, 2004); and 6) Berg balance scale (Berg et al, 1995) score ≥ 41. The exclusion criteria were 1) individuals with previous experience with VRHB systems; 2) individuals with severe dementia or aphasia; 3) individuals whose visual or hearing impairment did not allow the possibility of interaction with the system; 4) individuals with hemispatial neglect; and 5) individuals with ataxia or any other cerebellar symptom.

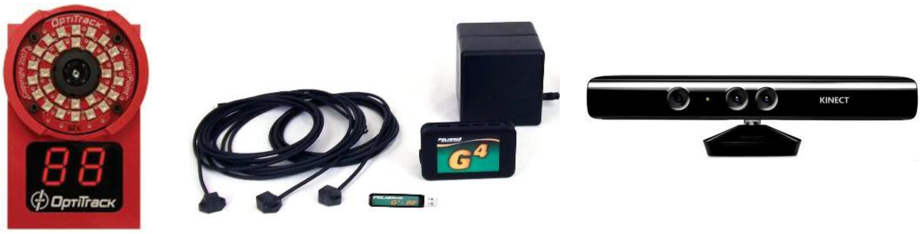
- *Physical therapists.* The inclusion criteria in the physical therapists group were 1) physical therapy degree; and 2) ≥ 2 years of experience in neurorehabilitation. Therapists with previous experience with VRHB systems were excluded.

2.2 Brief description of the tracking systems

Three different tracking solutions were used in this study: optical, electromagnetic, and skeleton tracking. The optical tracking consisted of two infrared cameras OptiTrack™ V100:R2 (NaturalPoint®, Corvallis) (Figure 1.a) aligned in the same plane. This setting allowed to locate spherical reflective markers present in the intersectional field of view of both cameras using epipolar geometry (Hartley et al, 2003).

A G4™ (Polhemus™, Colchester) was used as electromagnetic solution (Figure 1.b). Essentially, the tracking consists of an electromagnetic source and different sensors that are connected to a hub, which supplies them with power and transmits the tracking data to a PC. The sensors detect the electromagnetic field generated by the source and estimate their location and orientation (Raab et al, 1979).

With regards to the skeleton tracking, a Kinect™ and the Kinect for Windows SDK were used to track the body joints. This tracking solution estimates the depth information of the scene, detects the human silhouettes present in the depth images, and applies a statistical method to fit a skeleton in the silhouettes (Shotton et al, 2011).



(a) (b) (c)

Figure 1. *Tracking systems under study: (a) optical;(b) electromagnetic; and (c) skeleton tracking.*

A summary of the performance parameters of the tracking systems, principally defined by the manufacturer, is depicted in Table 1.

Table 1. *Characteristics of the tracking systems. *: Resolution, field of view, and wavelength are parameters of the optical tracking systems.*

Characteristic	**NaturalPoint® OptiTrack™ V100:R2**	**Polhemus™ G4™**	**Microsoft® Kinect™**
Measurements (cm)	Camera: 7.5x4.5x3.7 Marker: 4 (diameter)	Source: 10.2x10.2x10.2 Hub: 10.6x1.9x6.6 Sensor: 2.29x2.82x1.52	Camera: 7.5x4.5x3.7 (5.8x28.2x6.8 with the support base)
Weight (g)	Camera: 119.1 Marker: 8	Source: 725.7 Hub: 114.0 Sensor: 43.0	Camera: 590
Frequency (Hz)	100	120	30 (with 1 skeleton)
Latency (ms)	10	10 (in optimum conditions)	150-500 (Gieselmann, 2011)
**Resolution*	RGB: 640x480 (at 100 Hz) with 8 bits	-	RGB: 640x480 (at 30 Hz) with 8 bits Depth: 640x480 (at 30 Hz) with 11 bits
**Field of view (º)*	Horizontal: 46 Vertical: 35 (Default lens, 4.5mm F#1.6)	-	Horizontal: 57 Vertical: 43
**Wavelength (nm)*	850	-	850
Connections	Wireless	Sensor-Hub: Wired Hub-Source: Wireless (proprietary RF link at 2.4 GHz with frequency hopping architecture)	Wireless
Power supply	Camera: 5 V, 490 mA Marker: Passive	Source: 5 V, 1 A Hub: 5 V, 500 mA (rechargeable battery) Sensor: Passive	Camera: 12 V, 1.1 A
Cost ($)	1198 (including 2 cameras)	5250 (including 1 sensor)	249

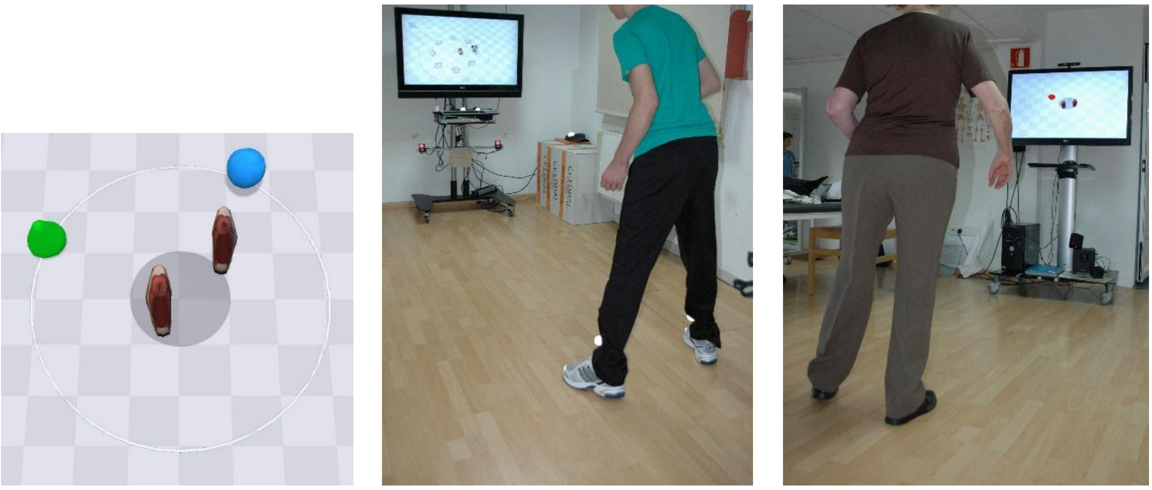
2.3 Virtual environment

A VR-based stepping exercise was used to assess the experiences of the participants of the three groups when using different tracking technologies. The VE consisted of an empty scenario consisting of a checkered floor whose center was indicated with a darkened circle. The participants were represented by two feet that mimicked the movements of their own feet in the real world with a third person perspective. Initially, both feet appeared in the center of the circle. Different items rose from the ground in the surroundings of the circle, and disappeared after a few seconds. The objective of the exercise was to step on the rising items with the nearer foot while maintaining the other foot (the support foot) within the boundaries of the circle. After stepping on the items, the leg had to be recruited towards the body and enter into the circle to allow stepping on the next item.

The ankle joints (tibiotalar) of the participants were located and transferred to the VE by the tracking systems. In the optical and electromagnetic solutions the joints were identified with reflective markers or electromagnetic sensors, respectively, fixed with a Velcro strip. The hardware setting of the VR system consisted of a standard PC, a 42" LCD screen, and one of the tracking systems described in the previous section.

2.4 Procedure

Three different VR units were installed in the physical therapy area of a neurorehabilitation center, each equipped with a different tracking system. The experiences of all the participants after using the three systems were collected through two ad-hoc questionnaires (A and B). Questionnaire A collected the experiences of healthy subjects and individuals post-stroke. Questionnaire B collected the experiences of physical therapists. The first four questions of both questionnaires evaluated the same topics.



(a) (b) (c)

Figure 2. *Virtual reality-based stepping exercise: (a) Snapshot of the virtual environment; (b) Participant interacting using the optical solution; (c) Participant interacting using the skeleton tracking solution.*

Participants belonging to the healthy and stroke group interacted with the stepping exercises in three 15-minute trials using the three tracking systems in counterbalanced order. The level of difficulty was determined by a physical therapist who supervised all the sessions, to define an attainable but challenging task. After each trial, participants filled questionnaire A. Questionnaire A consisted of six items that assessed 1) fixation speed of the sensors/markers, 2) ease of the calibration, 3) accuracy of the represented movements, 4) robustness, 5) comfort, and 6) order of preference. Responses to the first five items were rated on a 5-point Likert scale, where 1 means “very little/not at all” and 5 means “very much”. Responses to the last item were estimated as a percentage of preference.

The VR-based system was integrated in the physical therapy program. Patients who were attending a motor rehabilitation protocol in the neurorehabilitation center were assigned to train with the system according to their motor condition and expected benefits. Physical therapists monitored 45 training sessions with the VR-based exercise, 15 sessions with each tracking technology in randomized order. After the 45 sessions, the therapists, who were uninformed of the costs of the tracking systems during the entire study, were finally informed and filled in the questionnaire B for the optical, electromagnetic, and skeleton tracking. This questionnaire consisted of eleven items that assessed 1) fixation speed of the sensors/markers, 2) ease of the calibration, 3) accuracy, 4) robustness, 5) ease of fixation, 6) insensibility to changes in the clinical setting, 7) ease of assistance, 8) maintenance, 9) working range, 10) value for money, and 11) order of preference. As in questionnaire A, the first tenth items were rated on a 5-point Likert scale and responses to the last item were estimated as a percentage of preference.

2.5 Statistical analysis

Demographical comparisons among groups were performed with independent sample t-tests and Chi-squared or Fisher exact tests, as appropriate. Repeated measures analyses were performed using the non-parametric Friedman test ($\chi 2$, p values) to determine within-group differences between tracking systems (NaturalPoint® OptiTrack™, Polhemus™ G4™, and Microsoft® Kinect™). When the Friedman test yielded a significant effect ($p<0.05$), post hoc analysis was performed using a Wilcoxon signed-rank test for pairwise comparisons between tracking systems. The α level was set at 0.05 for all analyses. All analyses were computed with SPSS for Mac, version 20 (SPSS Inc., Chicago, USA).

3. RESULTS

After inclusion/exclusion criteria the healthy group consisted of 19 individuals (12 males and 7 females, 60.8±4.1 years old) and the stroke group consisted of 22 individuals (15 males and 7 females, 60.1±7.0 years old). The stroke group included ischemic (n=11) and haemorrhagic stroke (n=11), and presented a chronicity of 272.4±56.7 days. Of all the physical therapists working in the neurorehabilitation center, 14 therapists (6 males and 8 females, 31.8±2.4 years old) satisfied the criteria and accepted to be included in the study.

Table 2. *Scores of the subjective questionnaires. Only significant differences are stated. K=Microsoft® Kinect™, O=NaturalPoint® OptiTrack™, G4=Polhemus™ G4™. Friedman with Wilcoxon as post-hoc. *p<0.05, **p<0.001. Significance: > higher than, = same as.*

Issue	**NaturalPoint® OptiTrack™**	**Polhemus™ G4™**	**Microsoft® Kinect™**	**Significance**
Healthy, stroke individuals, and physical therapists				
A1/B1. Fixation speed of sensors/markers				
Healthy group	4.2±1.0	4.0±1.1	5.0±0.0	O=G , K**>O, K**>G
Stroke group	4.3±0.5	3.9±0.6	4.4±0.5	O*>G, O=K , K*>G
Professional group	3.6±0.8	3.2±0.7	5.0±0.0	O=G, K**>O, K**>G
A2/B2. Ease of calibration				
Healthy group	4.5±0.8	4.6±0.7	4.8±0.7	NS
Stroke group	4.3±0.6	4.4±0.5	3.0±0.6	O=G , O**>K, G**>K
Professional group	4.1±0.6	4.4±0.5	3.1±0.4	O=G , O**>K, G**>K
A3/B3. Accuracy				
Healthy group	4.7±0.5	3.7±0.9	4.3±0.8	O**>G, O*>K*, K*>G
Stroke group	4.2±0.7	3.9±0.8	3.4±0.7	O=G, O*>K, G*>K
Professional group	4.6±0.5	3.3±0.8	4.0±0.7	O**>G, O*>K, K*>G
A4/B4. Robustness				
Healthy group	4.5±0.6	4.7±0.4	4.0±0.8	G*>O, O=K, G**>K
Stroke group	3.9±0.7	4.3±0.7	3.4±0.7	G*>O, O*>K, G**>K
Professional group	4.0±0.8	4.6±0.5	3.3±0.8	G*>O, O*>K, G**>K
Healthy and stroke individuals				
A5. Comfort				
Healthy group	4.0±0.7	3.5±0.9	4.8±0.5	O*>G, K**>O, K**>G
Stroke group	4.0±0.5	3.3±0.6	4.7±0.5	O**>G, K**>O, K**>G
Professional group	-	-	-	-
Physical therapists				
B5. Ease of fixation				
Healthy group	-	-	-	-
Stroke group	-	-	-	-
Professional group	4.0±0.6	3.4±0.5	4.8±0.4	O*>G, K*>O, K**>G
B6. Insensibility to changes in the clinical setting				
Healthy group	-	-	-	-
Stroke group	-	-	-	-
Professional group	3.1± 0.6	3±0.8	3.7±0.5	O=G, K*>O, K*>G
B7. Ease of assistance				
Healthy group	-	-	-	-
Stroke group	-	-	-	-
Professional group	4.1±0.7	4.4±0.7	2.5±0.9	O**>K, G**>K, O=G
B8. Maintenance				
Healthy group	-	-	-	-
Stroke group	-	-	-	-
Professional group	4.4±0.7	3.3±0.9	4.9±0.3	O**>G, O=K, K**>G
B9. Working range				
Healthy group	-	-	-	-
Stroke group	-	-	-	-
Professional group	3.9±0.8	3.2±1.1	4.2±0.7	O*>G, O=K, K*>G
B10. Value for money				
Healthy group	-	-	-	-
Stroke group	-	-	-	-
Professional group	2.5±0.5	2.3±0.7	4.8±0.3	K**>O, K**>G, G=O
Healthy, stroke individuals, and physical therapists				
A6/B11. Preference (n, %)				
Healthy group	3 (15.8 %)	1 (5.2 %)	15 (79.0 %)	-
Stroke group	11 (50 %)	3 (13.6 %)	8 (36.4 %)	
Professional group	4 (28.6 %)	3 (21.4 %)	7 (50 %)	

Results of the three groups to the questionnaires showed that healthy subjects and physical therapists mainly preferred the skeleton tracking solution rather than the optical and electromagnetic solution (in that order). However, individuals post-stroke preferred the optical solution over the other options (Table 2).

4. DISCUSSION

Scores to the different items of the questionnaire are discussed below.

- *A1/B1. Fixation speed of sensors/markers.* All the groups reported the Kinect™ as the least time consuming system, followed by the optical and the electromagnetic solution. Despite the significant difference between the skeleton and the optical tracking reported by the healthy and professional group (0.8 and 1.4 in mean, respectively), individuals with stroke did not find this difference as relevant (0.1 in mean). The fixation speed of the electromagnetic sensors was reported to be the lowest by the three groups. Interestingly, the professionals evaluated it with the lowest score, which can be explained by the fact that they also had to be careful with the position of the wires to avoid tangles.
- *A2/B2. Ease of calibration.* No significant differences between tracking systems were reported by the healthy group. However, the stroke and professional group found the calibration for the skeleton tracking to be significantly more difficult than for the other systems ($p<0.001$), since it required the participants to move to be tracked. This fact made the task more difficult for individuals with stroke, who presented motor impairments, as reported by clinicians and themselves.
- *A3/B3. Accuracy.* The optical tracking system was reported to be the most accurate solution by all the groups ($p<0.05$), consistently with the results of the performance study. The same ranking order was found in the responses from healthy individuals and physical therapists. Individuals with stroke, however, reported the Kinect™ to provide the lowest accuracy ($p<0.05$). The presence of motor impairments could have led individuals with stroke to execute irregular movement patterns and postures that can affect the body parts recognition and skeleton fitting processes.
- *A4/B4. Robustness.* Similar conclusions can be inferred from the results of the robustness. All the groups defined the electromagnetic tracking solution as the most robust solution ($p<0.05$), followed the optical and the skeleton tracking system. Errors in the pose estimation could cause momentary maladjustments between the real and the virtual pose, which could be interpreted as a lack of robustness, especially by individuals with stroke and physical therapists, who reported the lowest scores (3.4 ± 0.7 and 3.3 ± 0.8, respectively).
- *A5. Comfort.* The skeleton tracking system, which did not require sensors, was evaluated as the most comfortable solution by healthy subjects and individuals post-stroke ($p<0.001$), followed by the optical and the electromagnetic solution. Differences between the optical and the electromagnetic tracking systems were also reported by the healthy ($p<0.05$) and stroke group ($p<0.001$). While the optical solution only required participants to wear reflective markers attached to their ankles, the electromagnetic solution also required them to wear a hub held to the waist of their pants, which was connected through wires to the sensors.
- *B5. Ease of fixation.* The professional group evaluated the skeleton tracking with the highest score, followed by the optical and the electromagnetic system (consistently with the scores in the fixation speed), which required therapists to fix the markers in the ankle joint of the patients. The electromagnetic solution, in addition, required the fixation of the hub and the careful placement of the wires in order to avoid tangles. The time and ease of fixation are crucial factors that must be minimized in clinical applications, where time is limited and should be dedicated to the physical therapy (Kwakkel, 2006; Han et al, 2013).
- *B6. Insensibility to changes in the clinical setting.* The therapists considered that the skeleton tracking system was the least susceptible system ($p<0.001$). However, the overall scores were low in comparison with other items. The optical solution was sometimes affected by reflections caused by chairs, room dividers, plinths, etc., elements commonly present in the clinical setting, or even by the sunlight. Even though these issues can be avoided by removing these elements of the field of view of the cameras or by closing the blinds, physical therapy units are dynamic areas where the spatial distribution is constantly changing and the sunlight is appreciated. The electromagnetic tracking system proved to be the most susceptible solution to the environmental changes.
- *B7. Ease of assistance.* The therapists reported that the electromagnetic tracking system was the solution that better allowed them to assist the patients. The physical principle of the G4™ made the performance of the system possible even when the therapists were between the source and the sensors. It allowed them to freely assist the patients from any position, and even to manipulate their extremities if needed. The optical tracking, on the contrary, required that the cameras had direct line-of-sight to the markers. The

assistance, although possible, had to be provided from behind. Similarly, the Kinect™ required direct line-of-sight with the participants' complete silhouettes. Since the statistical method to detect the body segments was trained with isolated human poses, when therapists were close to the patients, manipulating or touching them, the system was not able to fit a skeleton in the resulting silhouette. Therapists had to hide from the view of the Kinect™ in order not to affect the tracking, which derived in significant lower scores (2.5±0.9, $p<0.001$).

- *B8. Maintenance.* With regards to the maintenance, the therapists found that the need for recharging the hub of the electromagnetic tracking system after five to six hours of use was a limiting factor ($p<0.001$). The other tracking solutions did not required special maintenance.
- *B9. Working range.* The professional group reported that the skeleton tracking system provided the largest working area, followed by the optical tracking system and the electromagnetic solution, which had significant lower scores ($p<0.05$), consistently with the experimental results.
- *B10. Value for money.* The mass-produced Kinect™, which had the lowest price, achieved the highest score ($p<0.001$). Scores to the other tracking solutions were also consistent with their price.
- *A6/B11. Preference.* The healthy group mostly preferred the Microsoft® Kinect™ (79.0%), over the other tracking systems, which is consistent with their scores to the comfort item. Remarkably, this group did not experience significant problems when interacting with the system, as the Kinect™ is oriented towards healthy population. On the contrary, the stroke group mostly preferred the optical tracking system (68.2 %). The mentioned issues derived from a wrong skeleton fitting, more common in this group due to their motor restrictions, could have influenced their choice. These facts should be specially taken into account when working with individuals with stroke, since they are likely to present behavioural problems (Chemerinski et al, 2006), as irritability or depression, which can make this population particularly prone to frustration and reduce the benefits of rehabilitation (Flaster et al, 2013). In consequence, the use of the Kinect™ could be restricted to subjects with specific motor conditions. The therapists mostly preferred the skeleton tracking (57.1 %), slightly over the optical solution (35.7 %). This result could be explained as a trade-off between both systems. In spite the ease and speed of the Kinect™ startup and its ease of maintenance, the aforementioned issues with the Kinect™ can make the interaction of some patients difficult. The optical solution can overcome most of the interaction problems but it presents, however, some environmental restrictions (mainly light-related effects) that can affect their clinical use. An ideal situation allowing the use of these two tracking options, and the required space in the physical therapy unit, could satisfy all these requirements.

To summarize, our results show that subjective perceptions and preferences are from being constant among different populations, thus suggesting that these considerations, together with the performance parameters, should be also taken into account when designing a rehabilitation system. In general, the skeleton tracking system was preferred by therapists and healthy individuals, and by a great number of individuals post-stroke. With regards to the therapists, though the assistance with skeleton tracking system initially posed a challenge for them (reported as the main issue of the technology), once they knew its functional limits, they were able to provide assistance to the patients. This fact, together with its affordable cost, could have led them to finally adopt the skeleton tracking solution over the other systems, and can be the reason why they are using it currently in their daily practice.

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