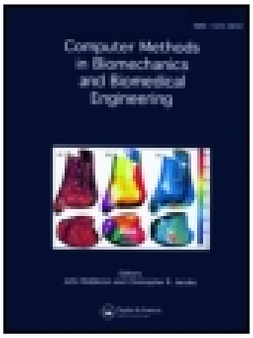

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Biomechanical and functional effects of shoulder kinesio taping® on cerebral palsy children interacting with virtual objects

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ABSTRACT
The reaching of objects is usually practiced by CP children in conventional or Virtual Reality-based therapies to enhance motor skill performance. Recently, Kinesio Taping® method has been studied to increase mechanical stability and improve functional movement of the upper limb; however, its influence on CP children's upper limb motion has been rarely quantified due to lack of sensory measurement. Therefore, in this paper, we evaluate the biomechanical and functional effects of applying shoulder Kinesio Taping® on CP children in the reaching-transporting of virtual objects, by using a low-cost tracking device, exact robust differentiation of data and a simple nonlinear biomechanical dynamic model of the trunk and arm.

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KEYWORDS
Biomechanical analysis; shoulder kinesio taping; CP palsy; virtual reaching task

Introduction

Cerebral Palsy (CP) often present difficulties to achieve tasks requirements that involve sensorimotor coordination such as reaching-grasping and transporting-releasing objects, which contribute to their disability and interfere with the development of their independent life skills. Occupational and physical therapy are the most common treatments offered to CP children aimed at promoting a better motor behavior. These therapies are commonly complemented with botulinum toxin, orthopaedic surgery, pharmacotherapy for muscle tone, orthoses. Notably, Kinesio Taping® (KT) stands for a relatively new and slightly less invasive complementary rehabilitation method that involves a combination of the applying tension along an elastic tape and its application over a stretched muscle. When the muscle returns to a neutral position, the elasticity in the tape gently lifts the skin creating convolutions or wrinkles on its surface, which may lead sometimes to visible wrinkles on the tape surface as well (Kase et al. 2003). These convolutions create a microscopic space between the skin and the tissues below, facilitating the flow of lymphatic fluid and release in pressure on the tissues underneath. It has been hypothesized that these effects can help relieve pain, prevent over-contraction, facilitate lymphatic drainage, and improve proprioception (Morris et al. 2013). This latter effect can result in a subsequent improvement in joint stability and movement control, as well as in motor coordination (Santos et al. 2017). In paediatric rehabilitation, and by selecting an appropriate shape, application direction and tension of the tape, KT has been commonly used to improve gross motor skills, upper limb function, hand dexterity, sitting posture and trunk control, and also to limit joint movement (Ortiz and Perez de la 2017). Although the growing popularity of KT, few scientific studies have been conducted to support its effectiveness in promoting upper limb functionality in CP pediatric patients, and most of them are pilot or case studies (Kaya Kara et al. 2015). In addition, there is limited evidence based on quantitative movement analysis and randomized control trials that KT improves upper limb function.

KT effects on motor function of CP children have been mainly assessed by means of clinical and functional scales (Kaya Kara et al. 2015), such as the Gross Motor Function Classification (GMFC) measure and Functional Independence Measure for Children (WeeFIM). However, a quite few number of studies have assessed KT effects by measuring kinematic variables of limbs, such as joint Range of Motion (ROM), or muscle activity (dos Santos et al. 2018). Moreover, to our knowledge, no study has

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considered the measurement of dynamic parameters that combined with kinematic parameters generate novel metrics for upper limbs performance, such as joint torques and energy expenditure. In this paper, we aim to contribute in this direction by measuring the kinematic and dynamic effects of applying KT on CP children to improve shoulder stability and control, and upward movement of the upper limb, in a reaching and transporting Virtual Task (VT).

Reaching tasks require a coordinated activation of multiple muscles involving a large number of degrees of freedom of the upper limb. Therefore, they have been used as experimental test in several studies to assess upper limb functionality or postural stability of CP children after a treatment (Camerota et al. 2014; Pavão et al. 2018) or for comparison with results of healthy children (Butler et al. 2010). Similarly, the present study makes use of a reaching task to evaluate the immediate biomechanical and functional effects of shoulder KT application. Unlike previous studies, and expecting to have greater KT effects, we consider reaching movements above shoulder level, followed by transporting movements to release the object in a final target. Moreover, the reaching-transporting task is performed in a virtual environment to make patients interact safely with the environment and arrange the experimental task in a faster and similar manner for all participants.

In summary, the purpose of this study is to use a portable and low cost motion tracking system and implement a real time biomechanical approach to analyze the evidence, in a quantitative way, of kinematic and dynamic biomechanical changes of CP children's upper limb in a reaching-transporting VT due to a shoulder KT application. To achieve the biomechanical assessment, it was developed a robotic-like nonlinear biomechanical dynamic model of the trunk and upper limb. This model is solved in real-time using a high-order Levant's robust differentiator (Levant 1998) that feeds smooth position, velocity and acceleration data from joint motion tracking positions, instead of a naïve Euler differentiator commonly used in this type of applications. A virtual reality application that integrates the biomechanical model, Levant's differentiator and two graphical interfaces was developed. Furthermore, kinematic and dynamic-based metrics were computed in real time by processing the kinematic variables recorded by the motion tracking system and dynamic variables generated by the forward biomechanical dynamic model. This study also evaluates the effects of KT in terms of task performance metrics and a clinical measure, in order to find out their consistency with those of the biomechanical analysis. In summary, arm motion was evaluated at four levels: functional, task performance, kinematic, and kinematic and dynamic cost functions.

Methods and materials

Participants

A doctor in rehabilitation medicine, a physical therapist, a graduate engineering student and twenty CP children (fourteen boys and six girls) were involved in the study. The doctor and therapist are Kinesio Taping® certified practitioners from the Kinesio University™. Children were from the Children's Rehabilitation Institute of Teleton (CRIT) in Saltillo, Mexico and were selected by using the center's healthcare database. All children matched the following inclusion criteria: (i) 6–13 years of age, (ii) mild motor impairment (level I or II on the GMFC System), (iv) normal cognitive function, and (v) signed written informed consent from his/her parents, and none met any of the following exclusion criteria: (i) allergy to Kinesio Tape or ingestion of drug(s) or controlled medication. Children were randomly assigned into one of two groups using a computer random number generator: Intervention Group (IG; $n = 10$) and Control Group (CG; $n = 10$). The minimum, maximum and median age of children were of 6, 13 and 8.4 years old in the IG, and 7, 12.8 and 7.8 years old in CG. This study was approved by the CRIT's medical Ethics Committee and has the ANZCTR identifier ACTRN12618000635268.

Procedures

Three consecutive procedures were conducted on CP children. The first consisted of measuring children anthropometric characteristics (body weight and length of upper limb segments) at their arrival time. The second procedure was a functional test of gross manual dexterity of the affected upper limb known as standard Box and Block Test (BBT). To further benefit the normal average shoulder flexion (about 10^0) in the BBT (Kontson et al. 2017), the box base was placed 12 cm higher than the table top. The third procedure consisted of a biomechanical evaluation of upper limb movements during a reaching-transporting VT. The therapist applied the first two procedures, and both the therapist and student conducted the third procedure. The second and third procedures were applied on the IG before (pre-test) and after

Figure 1. Kinesio taping® application.

(post-test) the KT application, whereas on the CG in pre and post-tests without KT.

IG received the KT application after finishing the pre-test and after their skin was properly cleaned with isopropyl alcohol to eliminate sebaceous oils and abraded skin cells. A beige Kinesio Tex Classic™ tape (5 cm width, 0.5 mm thickness, 100% latex-free and cotton fibers) was applied using a combination of techniques designed to promote functional use of the affected upper extremity of CP children, see Figure 1. With the children in a sitting position and assistance of the therapist, the tape was applied by the Doctor as follows:

- First strip (Y-shape with round edges): It was placed to provide mechanical correction at the glenohumeral joint. Its base was anchored to the coracoid process of scapula with 0% tension, with the shoulder in neutral position. Subsequently, and with the humeral head maintained in inward rotation, the strip's proximal end was applied to the posterior deltoid with 50% tension.
- Second strip (Y-shape with round edges): It was placed for stimulating deltoid muscle function. Its anchor was applied to the acromion with 0% tension. One tail was applied parallel to the anterior deltoid with 15% tension, with the shoulder abducted and externally rotated. The second tail was applied to the posterior deltoid with 15% tension, with the shoulder flexed, horizontally adducted and internally rotated. The end of both tails was applied with 0% tension.
- Third strip (I-shape with round edges): Last, it was applied for functional correction of muscles contributing to shoulder abduction. Its anchor was applied to the middle third of the clavicle with 0% tension. With the shoulder in abduction, the tape was stretched by 50% and only its end was stick with no tension at the middle third of the lateral side of the arm. Subsequently, and with the shoulder adducted to the trunk, the tape was adhered.

After applying each strip, the tape was rub energetically by hand to activate the adhesive. In this study, the Kinesio tape was applied and removed the same day, and its application was not used as a treatment modality. Moreover, the secondary effects of its application were not supervised.

The task of the third procedure consisted of reaching with the hand (represented as a small sphere) three virtual balls, then place them into a box in front of trunk (see Figure 2). The balls were located above shoulder level and at 80% arm length. Participants reached and transported firstly the ball closest to shoulder level, subsequently the second closest, and so on. The maximum required joints' ROM to perform the task were of approximately 40° in elbow flexion, 5° in trunk rotation, 110° in shoulder flexion (from a neutral position) and 90° in horizontal adduction (from a starting position of shoulder abduction to 90°). The available time for reaching and transporting a ball was of 30 s and 10 s maximum, respectively. When these time periods were exceeded, the ball automatically appeared at hand position or inside the box signalling completion of the corresponding phase. Each time a ball reached the box, a yellow star appeared on the screen along with a short cheer sound effect, as visual and auditory success clues. For the analysis, task was segmented into two sequential phases:

- Reaching phase: until hand reaches the ball
- Transporting phase: until hand places the ball into the target box.

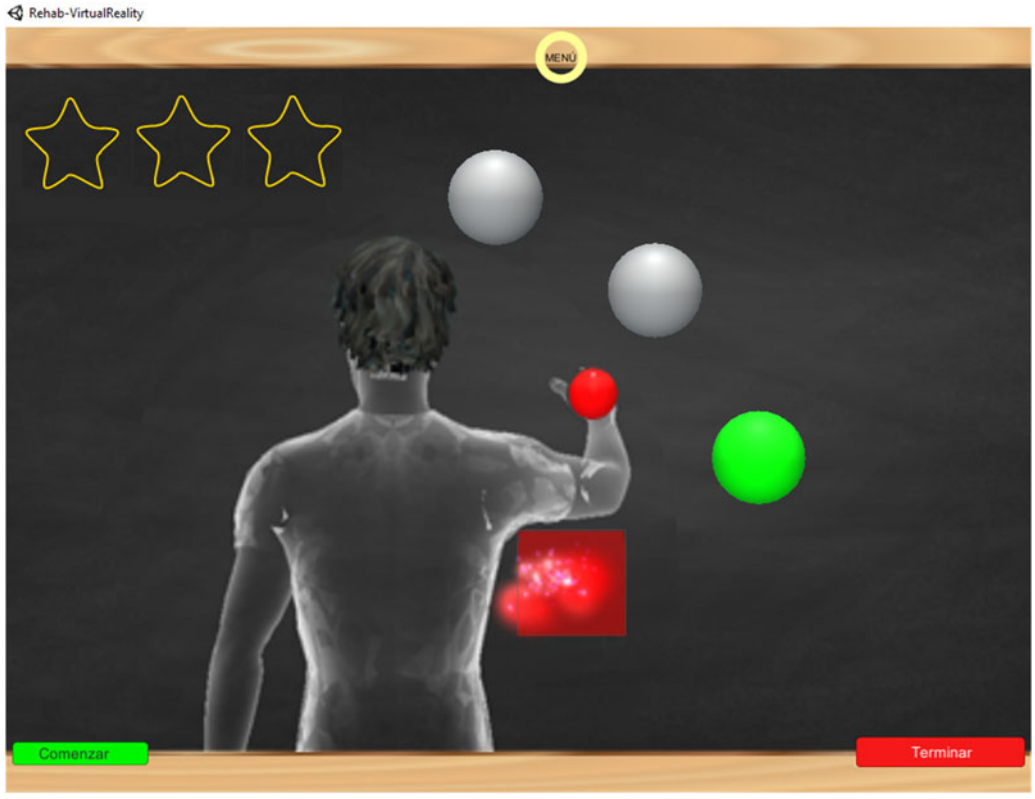

Figure 2. Virtual environment for reaching and transporting balls into a box. Small red ball represents hand position. Human avatar is shown to illustrate participant's body position

Before starting the VT children were comfortably seated 2 m in front of a motion capture sensor and monitor. They were verbally briefed about the nature and features of the task, and advised not to stand up or move their trunk during the task. Patients with poor sitting balance were fastened to the chair with Velcro bandage around the waist. Hemiplegic CP patients used their plegic upper limb to perform the task, while quadriplegic CP patients used their most affected upper limb, based on the therapist's judgement. Children performed a practice trial consisting of reaching-transporting two virtual balls. Subsequently, they performed four times the task, two as part of the pre-test and two as part of the post-test procedure. After the pre-test, a 15 min rest period was given. The task started with the hand on the thigh (0° shoulder elevation and 90° elbow flexion) and ended when reached ball inside the virtual target box, followed by a 2–5 s of rest with a "Go" audio signal for next attempt. Therapist verbally encouraged the children especially when they encountered difficulties to reach a ball, try to stand up or move the trunk to better reach the ball.

To display the virtual scene, a 50" flat-screen television was used, whereas the position and orientation of the upper body joints were recorded using a Kinect V2 sensor, which represents a cost-efficient alternative to expensive standard motion capturing systems that demand large facilities and expert trained technicians (Yang et al. 2002; Ancillao et al. 2017). Furthermore, recent studies have validated the Kinect as a reliable and valid clinical measurement tool. It was found that Kinect marker position measurements were equivalent to those of Vicon within an equivalence margin of 1.5 cm (Nichols et al. 2017), and that compared to the Vicon system, Kinect V2 can produce accurate measurements of trunk and shoulder position, but less accurate measurements of hand, knee and feet position (van Diest et al. 2014). Therefore, despite Kinect may face measurement limitations in hand and lower limbs movements, it yields upper limb (without including the hand) sensory data within the specified requirements of the present study.

The developed software application is composed of four main modules and was programmed in Unity 3D (Release 2018.2.2f1), as shown in Figure 3:

- Module M1 is devoted to the graphical rendering of the virtual environment and a Graphical User Interface for introducing patients' data.
- Module M2 calculates the rotation angles of the trunk and arm joints, by using a geometric formulation based on joints' position measurements.

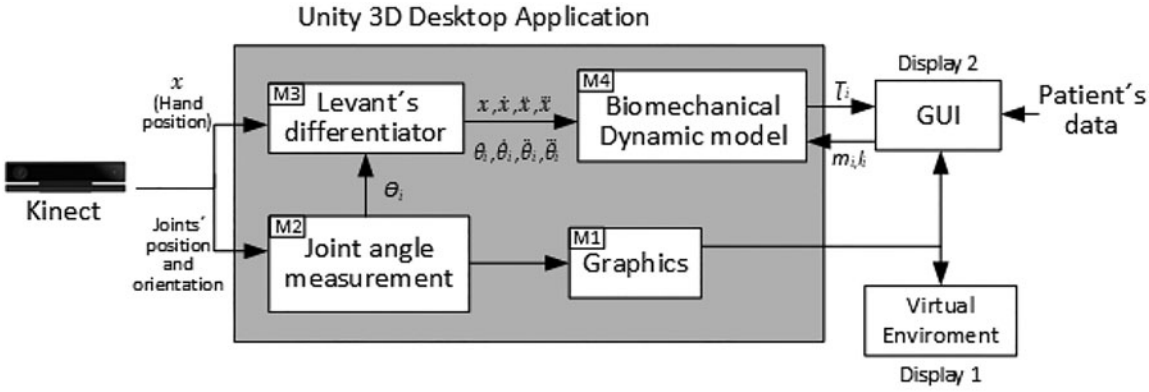

Figure 3. Modules of the software application.

- Module M3 receives kinematic data from M2 to estimate smooth velocities, accelerations and jerks of the hand and joints using Levant's differentiator.
- Module M4 computes the dynamic parameters of upper limb movements, such as torques, using the kinematic data generated in the third module.

Trunk and arm joint angles were calculated from the joints position estimation of Kinect by using a geometric approach and were input as a time series into Levant's differentiator module M3. This module is based on a high order sliding mode theory to yield smooth exact time derivatives in finite-time, despite the unknown dynamics and parameters that produced the time series. Figure 4 shows the derivatives of Kinect V2 data using the Levant and Euler differentiators. It can be clearly noticed that Levant's differentiator yields a physically significant second and third derivatives of Kinect's data, in contrast to Euler first order numerical approximation that neglects all non-linear terms. The lengths of the chain segments were defined equivalent to the dimension of the children's arm segments. That is, in one hand, the forward dynamic measurements conducted in M4 were achieved by using the Body Decomposition Approach to produce a parameterizable torques at each joint. On the other hand, the tensor of the moments of inertia for each segment (assumed as a rigid link), also referred to as angular mass or rotational inertia, as well the mass and center of mass of each segment were calculated as a percentage of the total child's body mass and segment length, respectively, by using the anthropometric data provided in (Winter 2005). The developed application runs in an independent thread at a constant sampled rate of 500 Hz, which meets the technical requirements to solve the powerful sliding mode algorithm that calculates the data time derivatives up to fourth order. In this way, also smooth jerk is obtained, which involves third order joint derivative.

Measures

Upper limb movement was analyzed at four levels:

1. Functional: BBT score was used to measure motor function of the upper limb.
2. Task performance: Task duration and accuracy were measured. The former was calculated as the time interval between movement onset and task completion and the latter as the average percentage balls reached and transported successfully.
3. Kinematic: Hand travel distance ratio, hand peak velocity and maximum ROM of joints were measured during the VT. The first measure was estimated as the ratio between the length of the real hand path and optimal trajectory. The second measure was the maximum first derivative of hand position data. The maximum ROM of the trunk rotation, flexion and horizontal adduction of shoulder, and elbow flexion achieved during the VT were calculated, and
4. Kinematic and dynamic cost functions: Hand jerk, angle jerk, sum of torques and absolute work achieved during the VT were calculated. The first two measures were estimated to evaluate movement smoothness at end-effector and joint level, respectively. The last two measures were estimated to quantify total force production and mechanical energy expenditure at the joint level, respectively. Cost functions were calculated as in Table 1 (Berret et al. 2011).

Data analysis

Results from Shapiro-Wilk tests revealed that all data were not significantly different from normal distribution

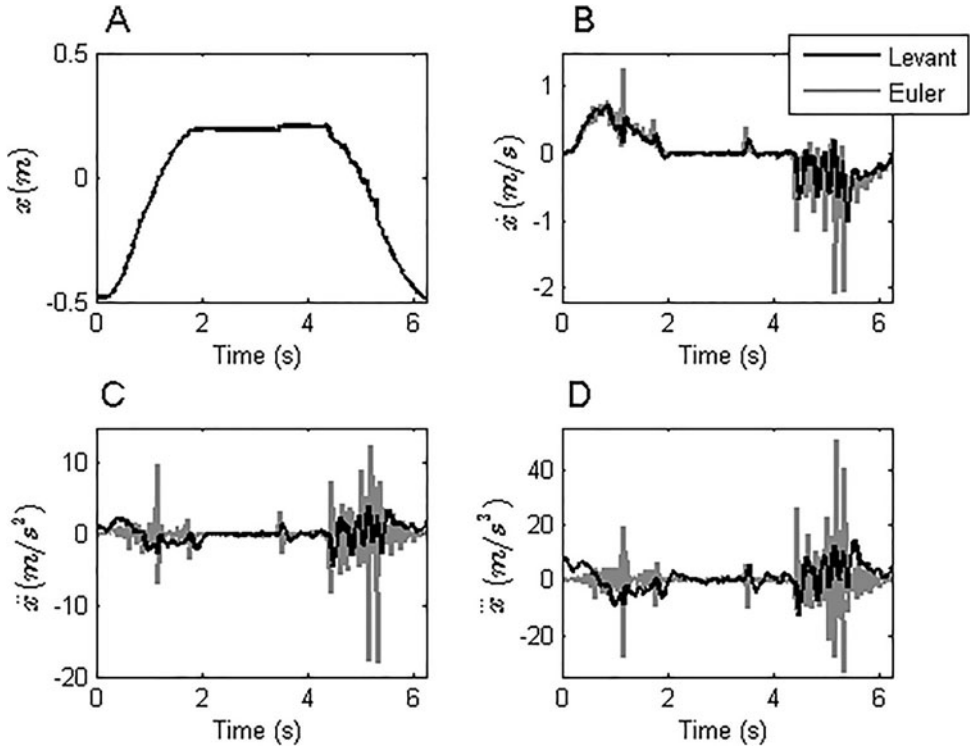

Figure 4. A) Signal recorded by the Kinect v2 sensor and its B) first, C) second and D) third derivatives, using the Levant (in black) and Euler (in grey) differentiators.

Table 1. Tested function costs and their equations.

C_i	Cost	Equation
C_1	Hand jerk $\left(\frac{m^2}{s^6}\right)$	$\int_0^T (\dddot{x}^2 + \dddot{y}^2 + \dddot{z}^2)dt$
C_2	Angle jerk $\left(\frac{1}{s^6}\right)$	$\int_0^T \sum_{i=1}^5 (\dddot{\theta}_i{}^2)dt$
C_3	Sum of torques (N^2m^2s)	$\int_0^T \sum_{i=1}^5 \tau_i{}^2 dt$
C_4	Absolute work (Nm)	$\int_0^T \sum_{i=1}^5 \lvert\dot{\theta}_i\tau_i\rvert dt$

Units are SI: s = second, m = meters, N = newton, T = subtask duration, $\dot{\theta}_i$=angle velocity, τ_i=torque acting on the i^{th}joint, $\dddot{\theta}_i$=third derivative of the i^{th}joint, $(\dddot{x},\dddot{y},\dddot{z})$= third derivative of hand position.

($p > 0.05$), and therefore meeting the normality assumption for parametric testing. BBT scores and maximum joints' ROM were compared within each group and pre and post-tests using paired t-tests. Task duration, accuracy, hand peak velocity and cost functions results were analyzed using a two-way ANOVA with group (CG and IG) as the between subject factor and with task phase (reaching and transporting) and session (Pre and Post) as the within subjects repeated factors. All the statistical analyses were carried out in R studio (version 1.1.456), using a 0.05 significance level.

Results

Average BBT scores and maximum joints' ROM achieved when performing the VT are shown in Table 2. BBT scores showed that only IG obtained a significant increase from pre to post-test ($t(9)$=0.9, $p < 0.01$). Joints' ROM results indicated that only IG showed a significant decrease in shoulder flexion from pre to post-test ($t(9)$=3.5, $p < 0.01$), getting close to the maximum required value of 110° in the post-test. None of the others joints' ROM of both groups changed significantly from post to pre-test.

Table 2. Pre and post-test BBT score and maximum ROM results.

Metric	Group	Pre-test	Post-test	*p*-value
BBT score	C	29.0 ± 5.8	30.9 ± 5.3	0.39
	I	19 ± 3.4	22.1 ± 4	0.009
Trunk rotation	C	13.5 ± 2.99	14.5 ± 3	0.7
	I	15.6 ± 2	15.8 ± 3.9	0.9
Shoulder flexion	C	119.2 ± 8.1	122.7 ± 8.7	0.3
	I	116.7 ± 5.1	110.3 ± 3.8	0.006
Shoulder horizontal adduction	C	128.2 ± 18	124.7 ± 22	0.5
	I	132.2 ± 22	125.7 ± 27	0.2
Elbow flexion	C	90.2 ± 15	83.7 ± 13	0.2
	I	96.8 ± 12	89.3 ± 11	0.19

I = Intervention, C = Control, all ROM's are in Degrees.

Average task performance results are displayed in Figure 5. Task completion time results revealed that only IG performed the task faster at post-test than at pre-test ($F(1,9)$ = 6.3, $p < 0.05$). Moreover, both groups needed significantly greater time to complete the reaching than the transporting task phase (CG: $F(1,9)$ = 6.3, $p < 0.05$; IG: $F(1,9)$ = 27.7, $p < 0.001$). Task accuracy results demonstrated that there is not difference between the accuracy level achieved by

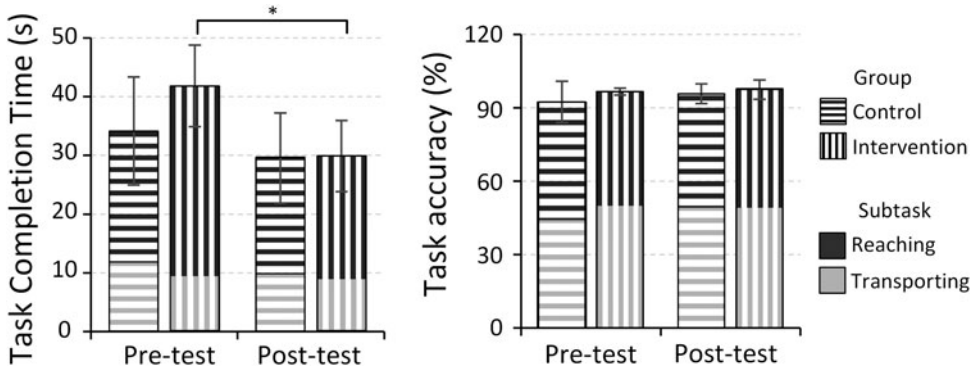

Figure 5. Mean pre and post task duration (left graph) and accuracy (right graph) achieved by IG and CG

both groups at the pre and post-test (CG: $F(1,9) = 1.2$, $p = 0.3$; IG: $F(1,9) = 0.13$, $p = 0.7$) and at the reaching and transporting task phases (CG: $F(1,9) = 0.4$, $p < 0.6$; IG: $F(1,9) = 5$, $p = 0.09$).

Average traveled distance ratio and peak velocity are shown in Figure 6. Results revealed that in both groups there was no a significant difference between the pre and post distance ratio traveled by the hand (CG: $F(1,9) = 3.4$, $p = 0.1$; IG: $F(1,9) = 0.6$, $p = 0.5$) and hand peak velocity (CG: $F(1,9) = 0.6$, $p = 0.44$; IG: $F(1,9) = 2.5$, $p = 0.15$). Furthermore, distance ratio traveled by the hand of both groups was significantly larger in reaching than in transporting task phase (CG: $F(1,9) = 11.9$, $p < 0.01$; IG: $F(1,9) = 10.8$, $p < 0.01$). However, peak velocity achieved by CG and IG in both task phases was similar (CG: $F(1,9) = 4.6$, $p = 0.06$; IG: $F(1,9) = 0.33$, $p = 0.6$).

Cost functions´ average results were all consistent, see Figure 7. They show that from post to pre-test, only IG yield smaller hand jerk ($F(1,9) = 10.4$, $p < 0.05$), angle jerk ($F(1,9) = 15.7$, $p < 0.01$), sum of torques ($F(1,9) = 9.6$, $p < 0.01$) and absolute work ($F(1,9)=12.3$, $p < 0.01$). Furthermore, both IG and CG yield smaller cost functions in the transporting than in the reaching task phase: hand jerk (CG: $F(1,9) = 6.2$, $p < 0.05$; IG: $F(1,9) = 27.7$, $p < 0.001$), angle jerk (CG: $F(1,9) = 7.5$, $p < 0.05$; IG: $F(1,9) = 5.6$, $p < 0.05$), sum of torques (CG: $F(1,9) = 5.7$, $p < 0.5$; IG: $F(1,9) = 12.4$, $p < 0.01$) and absolute work (CG: $F(1,9) = 15.1$, $p < 0.01$; IG: $F(1,9) = 13.9$, $p < 0.01$).

Discussion

The clinical measure results (BBT scores) revealed that only IG achieved a greater score in the post-test compared to the pre-test, suggesting that KT has an immediate impact on upper limb function. In contrast to this result, a pilot study (Yasukawa et al. 2006) showed that KT does not have an immediate effect on upper limb functional skills of children with varied diagnoses. However, the clinical measure (Melbourne assessment), clinical study design (quasi-experimental design), type of patients, and KT technique used in (Yasukawa et al. 2006) were different to those used in the present study, which makes it difficult to objectively compare the results. Interestingly, and as it will be discussed below, BBT results were consistent with completion time and maximum shoulder flexion results achieved during the VT.

Task performance results showed that only IG achieved the VT faster in the post-test compared to the pre-test, and both groups performed the task with a similar accuracy level in the pre and post-tests. These findings suggest that KT application has an immediate effect in shortening the time required to complete the VT, but not in improving the task accuracy.

Cost functions results demonstrated that only IG showed smoother hand and joint movements, produced smaller rotational forces and spend less mechanical energy in the post-test compared to the ones in pre-test. These results demonstrate that KT has a significant impact in minimizing kinematic and dynamic cost functions involved in the control of human arm movement.

Movement smoothness of joints and hand contribute to a more stable movements and therefore in reducing shoulder maximum flexion then lesser use of mechanical energy. This is shown through experimental data, wherein kinematic measurements reveal that only the dynamic maximum shoulder flexion of the IG decreased from pre to post-test, with post-test result near to that expected. Furthermore, the flexion movements of the shoulder during the VT were conducted against the gravity, which induced greater outward movement deviations (Furuya et al. 2015), making more evident the stability effect of the KT application.

The present results are generally in agreement with those reported in (Camerota et al. 2014), which is one of the few studies that examines the impact of taping

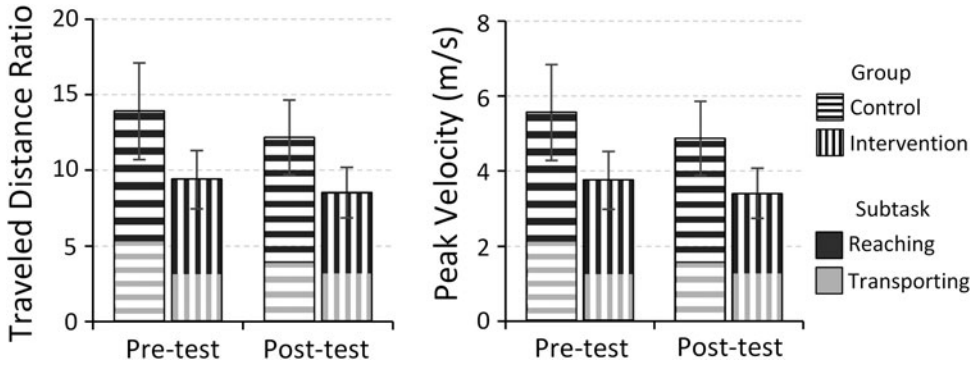

Figure 6. Mean pre and post hand traveled distance ratio (left) and peak velocity (right) achieved by IG and CG

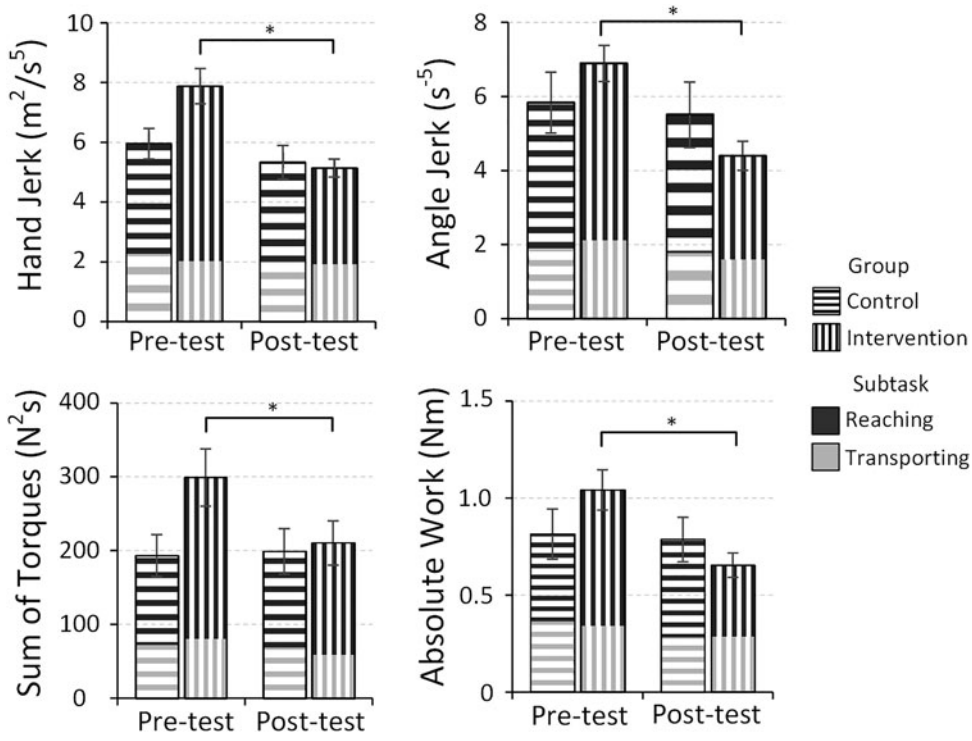

Figure 7. Mean pre and post hand jerk (upper-left), angle jerk (upper-right), sum of torques (lower-left) and absolute work (lower-right) achieved by IG and CG

in CP children by using motion analysis. They found that at the end of 2-weeks of taping application on the upper limbs, the movement of the affected limb was faster and smoother, and shoulder and elbow ROM were improved. However, it is difficult to establish an objective comparison with the results of this study, as they considered different taping method (Neuromuscular taping), muscle groups, evaluation period, task, and number of subjects (only an adult patient with hemiplegia).

Results also revealed that children from both groups covered greater distance ratios, had jerkier hand movements, produced higher torques and expended more energy in the reaching than in the transporting task phase. These results were expected since the balls´ position required mainly vertical movements against the gravity and above shoulder level, needing to travel longer distances, produce greater torques and therefore spending more energy. In fact, studies have found that supporting arm weight during reaching tasks improves movement smoothness in stroke patients (Bartolo et al. 2014).

Limitations

Although the present study elucidate some of the immediate effects of KT on CP children, further trials should considered a wider sample of CP children, with different motor severity levels and long-term follow up of KT.

Conclusion

The biomechanical motion analysis approach used to evaluate the effect of KT on upper limb motion of CP children during the interaction with virtual objects (located above shoulder level) reveals improvements in trunk and arm joints smoothness, hand-movement smoothness, joints´ force production (sum of joint torques), joints´ energy expenditure (absolute work) and in meeting the required shoulder flexion angle. These findings are in agreement with those obtained in the (modified) clinical test used to measure motor function of the upper limb (BBT). These results emphasize the importance of performing movement analysis at a kinematic and dynamic level in order to measure the subtle effects in the movement of the upper extremity produce by the KT application, difficult to observe in many cases due to the lack of sensory data, short period of KT application and subtle but definite differences between KT techniques.

Disclosure statement

Authors declare that they have no competing interests.

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