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Play with Objects in Children with Arthrogryposis: Effects of Intervention with the Playskin Lift™ Exoskeletal Garment

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Abstract

Children with arthrogryposis multiplex congenita (AMC) often exhibit arm movement impairments that can negatively impact activities of daily living, such as reaching, object exploration, object play, and self-care. This study evaluated the effects of intervention involving the Playskin Lift™ (Playskin) exoskeletal garment on arm function during object play for children with AMC. Seventeen children with AMC (5 males; 6-35 months at the beginning of the study) were tested in their homes biweekly with and without the Playskin throughout a 1-month Baseline, 4-month Intervention, and 1-month Post-Intervention. Within sessions (*assistive effects*), children contacted and manipulated objects more while wearing the Playskin; they also showed greater intensity, complexity, and variability of behaviors performed during free play, as well as increased play space and reduced number of compensatory arm and trunk flings to facilitate reaching. Across time (*rehabilitative effects*), children significantly improved their visual-manual coupling as well as their ability to lift objects from a surface and to manipulate objects using one hand; in addition, children exhibited greater multimodality, variability, and intensity of their play behaviors. Current results suggest the Playskin Lift™ may serve as an effective assistive and rehabilitative device to improve play for children with arm movement impairments.

Keywords: soft exoskeleton, object exploration, play, children, arthrogryposis

1 Introduction

1.1 Object Play in Children's Development

Early play with objects is important to inform infants about the properties of objects, the physical laws governing objects, and affordances among objects and infants' bodies (Bjorklund & Gardiner, 2011; Piaget, 1962; Singer, Golinkoff, & Hirsh-Pasek, 2006). Early play is defined as the active performance of a variety of behaviors with one or more objects, such as manipulation, banging, or stacking (Bjorklund & Gardiner, 2011). Early play with objects is enabled by the ability to attend to objects, to track them, to contact them via reaching and grasping, and to coordinate visual and manual behaviors (Barrett, Traupman, & Needham, 2008; Corbetta & Snapp-Childs, 2009; Libertus & Needham, 2010; Lobo & Galloway, 2013; McCarty & Ashmead, 1999; Needham, Barrett, & Peterman, 2002). Previous research has shown that object play is an important source of information gathering and learning, facilitating cognitive development, school readiness, and academic achievement (Bornstein, Hahn, & Suwalsky, 2013; Eppler, 1995; Gibson, 1988; Jouen & Molina, 2005; Lobo, Kokkoni, Cunha, & Galloway, 2015; Piaget, 1952; Rochat, 1989).

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Although the amount of play behavior performed by children is important for information gathering and learning, the level of variability in the behaviors performed is also important. Children have increased opportunities to problem-solve and learn when they observe the effects of multiple behaviors (Cunha et al., 2018; Dusing & Harbourne, 2010; Hadders-Algra, 2000; Piek, 2002). Children with physical disabilities may show less variability in their behavioral performance with objects (e.g., Lobo et al., 2015). As reduced variability of behaviors performed with objects likely results in diminished information gathering and learning opportunities (Bahrick, Lickliter, & Flom, 2004; Needham et al., 2002; Wilcox, Woods, Chapa, & McCurry, 2007), it may serve as an early indicator of developmental delay (Cunha et al., 2018; Prechtl, 1990; Sporns & Edelman, 1993).

The performance of play behaviors that provide information across multiple sensory modalities is also important for young children. Information about objects is more salient and learning can be enhanced when information is gathered across more than one sensory modality, as children compare and contrast visual, oral, tactile, auditory, temperature, and/or proprioceptive feedback (Bahrick et al., 2004; Corberta & Snapp-Childs, 2009; Gibson, 1988; Wilcox et al., 2007).

The ability to manipulate parts of an object or multiple objects is another important aspect of early play. Such types of manipulation, including inserting, removing, or stacking objects, are typically performed using both hands, with one hand holding or supporting and the other manipulating the object (Babik & Michel, 2016a; Kimmerle, Ferre, Kotwica, & Michel, 2010). Play with multiple objects informs children about object affordances, spatial relations among objects, and cause-effect relations (Babik & Michel, 2016a; Bruner, 1973; Greaves, Imms, Krumlinde, Dodd, & Eliasson, 2012; Fagard & Jacquet, 1989; Kimmerle et al., 2010). The planning and sequencing skills gained from this type of play are important for means-end problem solving tasks (Bower & Wishart, 1972; Diamond, 1991; Willatts, 1999), tool-use (Cox & Smitsman, 2006; McCarty, Clifton, & Collard, 1999), and cognitive development (Bremner, 2000; Gibson, 1988; Lobo & Galloway, 2008; Sommerville & Woodward, 2005; Soska, Adolph, & Johnson, 2010; Willatts, 1999).

Sensorimotor impairments may limit children's reaching and object play (Bos, van Braeckel, Hitzert, Tanis, & Roze, 2013; Grönqvist, Strand-Brodd, & von Hofsten, 2011; Lobo et al., 2015). Diminished amount, variability, and multimodality of play with objects can impact learning, problem solving, and cognitive outcomes (Cherkes-Julkowski, 1998; Cunha et al., 2018; Heathcock, Bhat, Lobo, & Galloway, 2004; Jongbloed-Pereboom, Janssen, Steenbergen, & Nijhuis-van der Sanden, 2012).

1.2 Arthrogryposis Multiplex Congenita

Arthrogryposis multiplex congenita (AMC) is a non-progressive congenital condition characterized by multiple joint contractures, significant muscle weakness, and reduced range of motion beginning in utero (Bamshad, Van Heest, & Pleasure, 2009; Staheli, Hall, Jaffe, & Paholke, 1998; Wallach et al. 2018). Children with AMC are often delayed in the development of antigravity arm movement, reaching, visual-manual coordination, object exploration, and bimanual engagement with objects (Babik et al., 2016; Babik, Cunha, & Lobo, under review), which might negatively impact motor and cognitive development, self-care, and quality of life (Cohen, Parmelee, Beckwith, & Sigman, 1986; Lawson & Ruff, 2004; Ruff, McCarton, Kurtzberg, & Vaughan, 1984). Commonly, children with AMC develop alternative strategies to interact with objects by using the mouth or feet.

As AMC typically affects the limbs in a symmetrical manner (Oishi et al., 2017; Wallach et al., 2018), many children with AMC initially have difficulty lifting both arms against gravity and bending them at the elbow (Babik et al., 2016). However, at an early age, these children may develop a strong hand preference (Babik, Movva, Cunha, & Lobo, under review), likely because it is adaptive to concentrate on learning to control the movement of only one arm, rather than attempting to manage both arms. This might result in a decrease or delay in the development of bimanual object play (Babik & Michel, 2016b) in children with AMC (Gibson, 1988; Jouen & Molina, 2005; Kimmerle et al., 2010; Lobo & Galloway, 2008, 2013; Rochat, 1989).

Since many children with AMC have difficulty lifting their arms against gravity (Babik et al., 2016), they often use compensatory trunk and arm flinging to transport their hands to objects. While implementing this compensatory strategy, children tend to extend the head back with their eyes directed upward rather than toward the hands and goal object. Although this strategy might help children achieve the goal of contacting objects, it reduces visual tracking and control of the hand(s), producing less flexible reaching patterns and negatively impacting the development of visual-manual coordination (Atkinson & Braddick, 2007; Petkovic, Chokron, & Fagard, 2016).

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In the most common type of arthrogryposis, Amyoplasia, children's arm function can be significantly improved with physical and occupational therapy to mobilize joints and promote muscle strengthening (Ferguson & Wainwright, 2013; Sells, Jaffe, & Hall, 1996).

1.3 Interventions with Exoskeletons

Exoskeletons have been used for rehabilitation to improve manual function in individuals with neuromuscular disabilities (Brewer, McDowell, & Worthen-Chaudhari, 2007; Haumont et al., 2011; Heo, Gu, Lee, Rhee, & Kim, 2012; Rahman et al., 2006, 2007). For pediatric populations, the Pediatric Wilmington Robotic Exoskeleton (P-WREX) was designed to provide anti-gravity support for the arms (Rahman et al., 2006, 2007). Positive assistive and rehabilitative effects of the P-WREX on reaching and object exploration have been shown in an 8 month old infant with AMC (Babik et al., 2016). While functional, the P-WREX was not an optimal device for younger populations because parents reported not preferring its weight, bulkiness, lack of comfort, and the fact that it restricted other activities, such as rolling and floor mobility.

The novel Playskin Lift^{TM} (Playskin) soft exoskeletal garment (Lobo et al., 2016), providing anti-gravity support to children's arms, was recently developed as a do-it-yourself (DIY) rehabilitation device (https://sites.udel.edu/move2learn/how-todiy/). The assistive and rehabilitative effects of the Playskin on children's performance in a standardized reaching task have been tested in infants born prematurely and/or with a brain injury and in young children with AMC (sample in the current study). Results suggested that wearing the Playskin improved a variety of skills related to reaching, including open-handed grasping, time contacting objects, functional reaching space, and multimodal object exploration for both infants born preterm and/or with a brain injury and children with AMC. Also, children's independent function improved across time due to intervention with the Playskin in the aforementioned populations (Babik et al., 2019; Babik et al., under review). Importantly, the Playskin was shown to be feasible for in-home, parent-guided intervention with infants and children, with parents rating the Playskin easy to use, comfortable, attractive, discrete, and not limiting children's mobility or other daily activities (Babik et al., 2019; Babik et al., under review).

1.4 Current Study

The current study is the first to evaluate play in young children with AMC and to assess the assistive and rehabilitative effects of the Playskin on play with objects for young children with AMC. The aim was to longitudinally evaluate children's visual, manual, and compensatory behaviors during object play with and without the Playskin across Baseline, Intervention, and Post-Intervention Phases. Object play was assessed in two conditions (play on the floor and at a surface) to reflect different natural play contexts. Based on previous research, we hypothesized that the Playskin would improve children's visual and manual abilities with objects when worn within sessions and intervention with the Playskin would improve children's independent function during free play across time (Babik et al., 2019; Babik et al., under review).

2 Materials and Methods

2.1 Participants

The study sample included 17 children with AMC [5 males; 13.9±8.7 months (range 5.8-35.0 months) at the beginning of the study]; 82.4% Caucasian, 11.7% African-American, and 5.9% Asian; 11.8% with gross household income $0-14,999, 5.9% with $15,000-24,999, 17.6% with $35,000-44,999, 29.4% with $60,000-79,999, and 35.3% with ≥$80,000. Children were included in the study if they could not independently lift their arms to at least 90° of shoulder flexion but had greater than 100 degrees of passive shoulder flexion; children were excluded from the study if they lacked independent head control. All children could independently support their own head in supported sitting; 12 children were able to sit independently, 5 needed external support while sitting. Active range of shoulder flexion against gravity was 39.0±38.8 degrees at the first visit. Participants continued to receive any ongoing early intervention services throughout the study. Recruitment of participants, informed consent, and data collection were conducted in accordance with the regulations set by the [MASKED] Institutional Review Board. Participants received monetary compensation of $50 at the completion of the study.

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2.2 Materials

The current study implemented an intervention using a novel, passive exoskeletal garment, the Playskin Lift™, that can provide variable levels of anti-gravity assistance for children with movement impairments birth to 3 years old (Lobo et al., 2016). The Playskin (Figure 1A) uses springs of bundled steel wires inserted into vinyl tunnels along the sleeves of a soft garment to assist in raising users' arms through 90° of shoulder flexion; users may vary the number and diameter of the wires in the inserts to alter the level of support provided.

2.3 Study Design

The ABA single-subject design implemented included 1 month of Baseline, 4 months of Intervention, and 1 month of Post-Intervention. The purpose of the *Baseline Phase* was to establish the initial level of children's object exploration during free play activities prior to intervention; the Playskin was used only during assessments. During the *Intervention Phase*, parents were trained via demonstration and written instructions (see Supplementary Materials) by a researcher with expertise in child development to use the Playskin for structured intervention activities (30-45 minutes daily) to encourage children to reach for objects placed at different heights and to promote free play while wearing the Playskin (Lobo & Galloway, 2008). Parents were instructed to alternate the level of support provided by the Playskin within each training session, switching among inserts to support the arms at approximately 30°, 60°, or 90° of shoulder flexion with the goal of allowing children to explore their movements and improve their strength across different areas of the play space. The *Post-Intervention Phase* allowed for evaluation of retention of intervention effects; due to ethical concerns, families kept their Playskins but were no longer expected to continue performing the daily structured intervention activities.

2.4 Procedures

All children were tested biweekly in their homes throughout all study phases during semi-structured free play with a standard set of toys appropriate for young children within the age range of this study (Figures 1B & C) while sitting on the floor (FLOOR assessment; 5 minutes; Figure 2A) and while sitting at a surface (SURFACE assessment; 5 minutes; Figure 2B). Children were free to choose any toy(s) to interact with and engage in any manipulations they wanted. Researchers did not interfere with the children's play. During the FLOOR assessment, contingent on each child's independent sitting ability, children sat on the floor either independently or supported by pillows. During the SURFACE assessment, children were seated in a child booster seat or high chair at a table. The level of seating support was consistent for each child throughout the duration of the study.

In each assessment (FLOOR and SURFACE), children's free play behaviors were assessed at each visit without (OFF condition) and with (ON condition) the Playskin; the order of conditions was alternated at each visit to avoid biases related to task familiarity or fatigue. For the ON condition, inserts were utilized that assisted each child's arms to approximately 70° of shoulder flexion. The study set-up was consistent across participants and testing sessions. Children were tested only while in a positive or neutral mood, otherwise the testing would be rescheduled. Assessments were video recorded using two cameras providing frontal and side views of the child; videos were later synchronized for behavioral coding with OpenSHAPA software.

2.5 Measures

Behavioral coding produced the following outcome variables: 1) *Unimanual Contact* – any part of the child's one hand contacting any object; 2) *Bimanual Contact* – any parts of both hands contacting the same or different object(s); 3) *Supported Contact* – hand contacting an object supported by another part of the child's body or a surface (e.g., floor, table, child's leg, or chest); 4) *Suspended Contact* – hand contacting an object not supported by other parts of the child's body or a surface; 5) *Unimanual Toy Manipulation* – play with a movable part of one object or interacting with two objects (e.g., inserting, taking out, pushing, stacking, spinning, or banging) with one hand; 6) *Bimanual Toy Manipulation* – play with a movable part of one object or interacting with two objects with both hands; 7) *Looking at the Toy(s)* – eyes directed towards one or more objects; 8) *Looking During Unimanual Contact* – eyes directed towards an object while contacting it with one hand; 9) *Looking During Bimanual Contact* – eyes directed towards an object while contacting it with both hands; 10) *Looking During Supported Contact* – eyes directed towards an object being contacted while supported by another part of the child's body or a surface; 11) *Looking During Suspended Contact* – eyes directed towards an object being contacted without support from another part of the body or a surface; 12) *Looking During Unimanual Toy Manipulation* – eyes directed towards an object while manipulating it with one hand;

13) *Looking During Bimanual Toy Manipulation* – eyes directed towards an object while manipulating it with both hands (variables 8-13 represent multimodal exploration); 14) *Bouts of Exploration* – number of transitions among behaviors per minute (behavioral intensity); 15) *Time Performing Single Behaviors* – performance of one behavior in isolation (e.g., looking at toy); 16) *Time Performing Combined Behaviors* – performance of more than one behavior simultaneously (e.g., looking during unimanual contact; represents behavioral complexity); 17) *Variability of Single Behaviors* – percent of the total possible single behaviors actually performed by the child; 18) *Variability of Combined Behaviors* – percent of the total possible combinations of behaviors actually performed by the child; 19) *Either Hand at the Head Level* – child held either hand at head level; 20) *Either Hand at the Chest Level* – child held either hand at chest level; 21) *Either Hand at the Hip Level* – child held either hand at hip level; 22) *Arm Flings to Reach the Toy* – swinging movement of an arm toward an object; 23) *Trunk Flings to Reach the Toy* – forward or backward swinging movement of the trunk to facilitate arm fling or reaching for objects with the mouth.

A custom program (Filemaker, Inc.) was used to detect overlapping occurrences of behaviors to produce variables 2, 6, and 8-21. Variables 1-13, 15-16, and 19-23 were calculated as percentage of the assessment time (dividing each behavior's duration by the total assessment time). Data were coded by trained undergraduate and graduate research assistants. Twenty percent of the data were re-coded to evaluate intra- and inter-rater agreement with a primary coder, both of which were ≥85% based on the equation [Agreed/(Agreed+Disagreed)]*100.

2.6 Statistical Analyses

All statistical analyses were conducted using Hierarchical Linear and Nonlinear Modeling Software (HLM; Raudenbush, Bryk, Cheong, Congdon, & du Toit, 2004), the most appropriate technique for longitudinal designs as it accounts for non-independence among multiple observations per participant. Statistical results at $\alpha \leq .05$ were considered significant, whereas those at $\alpha \leq .10$ were considered as trending toward significance.

2.6.1 Assistive Effects of the Playskin on Children's Play Performance

Assistive effects represent an improvement in performance within study phases while wearing the Playskin. Differences in children's mean performance between OFF and ON data were evaluated by regressing each outcome variable on the *Condition* variable (0 = OFF; 1 = ON) within each study phase (Baseline, Intervention, Post-Intervention).

2.6.2 Rehabilitative Effects of the Playskin on Children's Play Performance

Rehabilitative effects represent an improvement across time in children's independent performance (when not wearing the Playskin) as a result of intervention with the Playskin. Only OFF data were used to assess the change in children's independent function across time. Functional change in play ability across the three study phases was evaluated by regressing each outcome variable on dummy-coded phase variables (*B/I* – comparing children's mean performance between Baseline and Intervention; *B/PI* – comparing children's mean performance between Baseline and Post-Intervention; Baseline being a reference phase).

3 Results

Summarized observed data for the FLOOR and SURFACE assessments comparing children's performance during the Baseline, Intervention, and Post-Intervention Phases are presented in supplementary materials Figure S1.

3.1 Assistive Effects of the Playskin on Children's Play Performance

Detailed statistical results on the assistive effects of the Playskin are reported in the supplementary materials Table S1 and summarized in Figure 3.

In the *FLOOR assessment*, during *Baseline*, significant improvements while wearing the Playskin were observed in children's ability to lift toys from the surface, manipulate toys unimanually and bimanually, look at toys during bimanual or suspended contact, look at toys during unimanual and bimanual manipulation, bouts of exploration per minute, percent time performing combined behaviors, as well as variability of both single and combined behaviors. Also, while wearing the Playskin, children significantly increased their play space, lifting their hand(s) more to the

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chest and head levels, rather than keeping them at the hips. Importantly, even brief exposure (10 minutes total for the FLOOR and SURFACE assessments) to the Playskin without regular intervention during Baseline significantly reduced the performance of compensatory arm and trunk flings while reaching for toys.

During the *Intervention Phase* while wearing the Playskin, children showed significant improvement not only in lifting toys from the surface, but also contacting toys with both hands. Also, children exhibited more looking during bimanual and suspended contact and more looking during bimanual toy manipulation, enriching multimodal exploration. While wearing the Playskin, children significantly increased the intensity and variability of their object exploration, exhibiting a greater number of bouts of exploration per minute, combining different behaviors, and showing increased variability in the number of individual and combined behaviors performed. The benefits of the Playskin on children's play space and decreased trunk flings remained during the Intervention Phase.

After the intervention, children's unassisted (OFF condition) performance of many behaviors (e.g., unimanual, bimanual, supported, and suspended contacts; unimanual and bimanual manipulation; bouts of exploration per minute; percent time performing single and combined behaviors; lifting the hand(s) to chest or head level) showed improvements, so that during the *Post-Intervention Phase*, no significant differences between the OFF and ON conditions were identified in for these behaviors. However, during the Post-Intervention Phase, children's variability of single and combined behaviors continued to increase, a positive developmental sign.

In general, playing at the table in the *SURFACE assessment* was more challenging for children with AMC than playing on the floor perhaps because of the additional friction created by the surface and limited ability to use compensatory arm and trunk flings for reaching. Using the Playskin during the *Baseline Phase* improved children's unimanual and supported contacts, bimanual toy manipulation, looking at the toy(s) during unimanual or supported contact, and time performing combined behaviors. Moreover, brief exposure to the Playskin decreased the time the hand(s) were at the hip level, but did not significantly improve lifting the hand(s) to the chest or head level.

During the *Intervention Phase*, an improvement while wearing the Playskin was observed in children's performance of not only unimanual and supported, but also suspended contact, meaning that the intervention improved children's ability to lift the toys from the table. In the Playskin, children also showed more unimanual toy manipulation, looking at toys during suspended contact and unimanual manipulation, bouts of behavior per minute, time performing combined behaviors, and variability of combined behaviors. The intervention improved children's ability to lift the hand(s) at the chest level and reduced arm and trunk flings. During the *Post-Intervention Phase*, improvements in percent time looking at toys and variability of combined behaviors were observed; at the same time, there was further reduction in arm flinging.

3.2 Rehabilitative Effects of the Playskin on Children's Play Performance

Detailed statistical results on rehabilitative effects of the Playskin are reported in the supplementary materials Table S2 and summarized in Figure 4. Children improved their active range of shoulder flexion against gravity from 39.0±38.8 degrees at the first visit to 84.0±44.5 degrees at the end of intervention.

In the *FLOOR assessment*, children's independent function (OFF condition) during the Intervention Phase improved significantly relative to the Baseline Phase for suspended contact, unimanual toy manipulation, looking during supported or suspended contact, and looking during unimanual manipulation. As a result of the intervention, children decreased their performance of single behaviors and increased time performing combinations of behaviors, while increasing the variability of the single and combined behaviors they performed. Also, children significantly increased the time they held their hand(s) at head level.

There was a significant retention of the intervention effects and a steady improvement in children's independent function during the Post-Intervention Phase relative to the Baseline Phase. Children spent more time performing unimanual and supported contact, unimanual toy manipulation, looking during unimanual or supported contact, and looking during unimanual toy manipulation. Importantly, children increased the number of bouts of exploration they performed per minute, time performing combinations of behaviors, and variability of single and combined behaviors, while reducing their time performing single behaviors.

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In the *SURFACE assessment*, without the assistance of the Playskin, during the Intervention Phase relative to the Baseline Phase, children spent more time performing unimanual contact and looking during unimanual or supported contact; they also reduced time performing single behaviors while increasing time performing combinations of behaviors and increased the variability of single and combined behaviors performed. There was a decrease in time with the hand(s) at the hip level; however, this did not correspond to a significant improvement in lifting the hand(s) to the chest or head level.

Similar to the assessment of play on the floor, while playing at the table, during the Post- Intervention Phase relative to the Baseline Phase, children retained and further improved their abilities for unimanual and supported contact, unimanual toy manipulation, looking at the toy(s), looking during unimanual, supported, or suspended contact, and looking during unimanual toy manipulation. Also, children continued performing a greater number of exploration bouts per minute, spent more time performing combinations of behaviors (while reducing the time spent performing single behaviors), and increased the variability of the single and combined behaviors they performed.

4 Discussion

The goal of the current study was to comprehensively evaluate the assistive and rehabilitative effects of the Playskin Lift^{TM} exoskeletal garment on object exploration during free play in young children with AMC.

4.1 Assistive Effects of the Playskin on Children's Play Performance

4.1.1 FLOOR Assessment

While seated on the floor, many children with AMC in this study were able to contact objects supported on the floor using only one hand when they were not provided assistance. Wearing the Playskin significantly improved children's ability to lift toys from the floor and raise them to head or chest level, increasing their play space beyond hip level and into an area that better enables visual-manual coordination. Also, the anti-gravity support provided by the Playskin allowed children to engage both hands more equally in free play with toys, thus, we observed increased bimanual contact time in children when they wore the Playskin.

In accord with previous research showing the positive relation between bimanual reaching and bimanual object manipulation (Babik & Michel, 2016b), in the current study, wearing the Playskin improved not only the ability to contact objects bimanually, but also improved bimanual object manipulation. This type of activity allows children to engage in more complex actions with objects that afford differentiation of activity between the hands and permit more advanced learning opportunities, such as those related to concepts of in/out, object permanence, and cause-effect that are important for language and cognitive development (Babik & Michel, 2016a; Bonawitz et al., 2010; Bruner, 1973; Greaves et al., 2012; Fagard & Jacquet, 1989; Iverson, 2010; Kimmerle et al., 2010).

The improvements in reaching and object contact corresponded with increased visual attention; this visual-manual coupling would likely improve children's visual-manual coordination, resulting in further improvement in reaching and object play (Barrett et al., 2008; Corbetta & Snapp-Childs, 2009; McCarty & Ashmead, 1999; Thelen, 1990). Observing the effects of their actions on objects may also advance the intentionality and goal-directedness of children's object exploration (Sommerville & Woodward, 2005; Sommerville, Woodward, & Needham, 2005).

While wearing the Playskin, children were more likely to perform combinations of behaviors (e.g., touching or manipulating objects while looking at them), which permitted them to collect more enriched information about objects' properties, affordances, and relations among them using multiple sensory modalities (Bahrick et al., 2004; Corberta & Snapp-Childs, 2009; Gibson, 1988; Wilcox et al., 2007). Oral exploration could add another enriching modality to the children's repertoire, but this behavior is extremely challenging for children with AMC and was almost never observed in the current sample. In the Playskin, children also increased the intensity and variability of their exploration, which may also allow them to further advance their learning and cognitive development (Cunha et al., 2018; Dusing & Harbourne, 2010; Hadders-Algra, 2000; Piek, 2002).

Importantly, while wearing the Playskin, children significantly decreased their use of arm and trunk flinging to reach for toys. The reduction in this compensatory strategy might enable further improvements in children's visual tracking, hand control, and visual-manual coordination (Atkinson & Braddick, 2007; Petkovic et al., 2016). Interestingly, the reduction in the use of arm and trunk flinging would happen almost immediately after the Playskin was donned; thus, children were able to re-evaluate their body affordances and change their body dynamic quickly during free play in the Playskin.

4.1.2 SURFACE Assessment

Sitting at a table proved to be a more challenging context for play. Without assistance, many children had difficulties contacting objects supported on the table even with only one hand. Wearing the Playskin improved children's ability to contact objects unimanually without lifting them from the table. Only during the Intervention Phase was there a significant improvement in the ability to lift objects from the table and raise them to chest and, sometimes, to head level. Similar to play at the floor, while wearing the Playskin at a table, children showed greater intensity, multimodality, and variability of their exploratory behaviors. Also, there was a significant reduction in the use of arm and trunk flinging during the Intervention Phase.

4.2 Rehabilitative Effects of the Playskin on Children's Play Performance

4.2.2 FLOOR Assessment

As a result of the intervention, children significantly improved their independent ability to lift objects from the floor, manipulate objects using one hand, and couple visual and manual behavior. Improved arm function allowed children to increase the intensity, variability, and multimodality of their exploration. Importantly, after the completion of the intervention, there was retention of these improved abilities. No significant rehabilitative effects were identified for children's ability to raise their hands to the levels of the chest or head, or to decrease their compensatory arm and trunk flings.

4.2.2 SURFACE Assessment

Intervention with the Playskin improved children's independent ability to touch objects with one hand and to couple visual and manual behavior; it also increased the intensity, variability, and multimodality of children's play behavior. Again, there was retention of these improved abilities post-intervention. Without assistance, children did not show a significant improvement in their ability to hold their hands higher in their play space or to reduce their compensatory arm and trunk flings.

We propose that antigravity support from the Playskin allowed children to perform some challenging behaviors that they could not perform without assistance (e.g., reaching for toys presented at the chest or eye level, bimanual manipulation of toys). Such achievements increased children's motivation to move more and explore toys. Additional practice may have improved muscle strength, which, in turn, may have increased children's active range of motion. In this way, assistive effects of the Playskin may have translated into rehabilitative effects.

4.3. Limitations

It is possible that the improvements in children's play behaviors could be attributed to maturation or to the play component of the intervention alone, rather than to the Playskin in combination with the intervention. The current study design did not allow us to effectively separate the effects of the Playskin, intervention activities, and maturation. However, the children, many with very limited reaching abilities, were enrolled into this study at varying ages between 6 and 35 months, well after the typical onset of reaching (3-5 months; Lee, Liu, & Newell, 2006; Michel & Harkins, 1986; von Hofsten & Lindhagen, 1979) and object manipulation (6-12 months; Kimmerle, Mick, & Michel, 1995; Ruff, 1984) abilities. The fact that, despite their variable ages, participants showed significant improvements during the Intervention and Post-Intervention Phases relative to the Baseline Phase suggests that the changes were triggered by the intervention with the Playskin, rather than maturation. The replication of effects across multiple participants of varying ages is a strength of the current single-case study design that improves its internal and external validity (Kratochwill & Levin, 2014).

Furthermore, while it is possible that the play component of the intervention alone might have resulted in the improvements observed, it is not likely, as, since birth, the participants were all consistently receiving early interventions designed to encourage play activities (Lobo & Galloway, 2008; Ulrich, 2010). Therefore, it is likely the observed rehabilitative effects can be attributed to intervention with the Playskin.

Also, note that due to ethical concerns, participating families were allowed to keep and use the Playskin during the Post-Intervention Phase. This may have affected the estimated carry- over effects after the end of intervention.

4.4 Conclusions and Clinical Implications

The results of this study suggest that the Playskin Lift™ may serve as an effective assistive and rehabilitative device to improve activity in children with AMC. The Playskin improved children's play activity when worn within sessions. Daily home intervention with the Playskin guided by caregivers improved independent arm function across time; it also increased bimanual object manipulation, multimodal exploration of objects, and variability of the play behaviors performed, thus, facilitating children's opportunities to gather richer, more sophisticated information about objects during free play (Bahrick et al., 2004; Corberta & Snapp- Childs, 2009; Cunha et al., 2018; Gibson, 1988; Needham et al., 2002; Wilcox et al., 2007). As a result, the Playskin has the potential to positively affect not only children's motor outcomes, but also their cognitive development, self-care abilities, and overall quality of life (Bornstein et al., 2013; Gibson, 1988; Jouen & Molina, 2005; Nelson, 1999; Overland, 2011; Piaget, 1952).

The Playskin is an accessible device that is feasible for implementation into early intervention programs in natural settings for children with arm weakness or arm movement impairments. It is likely that pairing the Playskin with targeted intervention activities is a key to achieving optimal rehabilitative effects across time. Arm support devices, like the Playskin, that can provide variable levels of antigravity support to match the changing abilities of users may have the potential to improve activity performance and learning for children with a variety of diagnoses, including preterm birth, brain injury, stroke, cerebral palsy, and brachial plexus palsy (e.g., Babik et al., 2019). Future research should further evaluate the effectiveness of the Playskin exoskeletal garment for improving object exploration and play abilities in these populations.

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Figure Legends

Figure 1. The Playskin Lift™ exoskeletal garment (A) with vinyl tunnels under the sleeves for placement of springy supportive inserts (at the bottom) and arm straps (black) to maintain inserts aligned directly under the arms; toys used during the FLOOR (B) and SURFACE (C) assessments

Figure 2. Child wearing the Playskin during the free play assessment on the floor (A) and at a table (B)

Figure 3. ***Assistive effects*** of the Playskin Lift™ on the outcome variables during the FLOOR and SURFACE assessments. Black cells represent significant change ($p \leq .05$) while wearing the Playskin; grey cells signify marginally significant effects ($p \leq .10$); white cells denote no significant effect. NEG = negative, or lower values for the ON condition compared to the OFF, otherwise values for the ON condition are higher than those for the OFF. Note that the negative estimates included the behaviors that demonstrated less sophistication, a smaller play space, and poorer coordination. B = Baseline; I = Intervention; PI = Post-Intervention

Figure 4. ***Rehabilitative effects*** of the Playskin on the outcome variables during the FLOOR and SURFACE assessments. Black cells represent significant effects ($p \leq .05$); grey cells indicate marginally significant effects ($p \leq .10$); white cells mark no significant effect. NEG = negative, or lower values for the ON condition compared to the OFF, otherwise values for the ON condition are higher than those for the OFF. Note that the negative estimates included the behaviors that demonstrated less sophistication, a smaller play space, and poorer coordination. B to I = change in the mean performance from Baseline to Intervention; B to PI = change in the mean performance from Baseline to Post-Intervention

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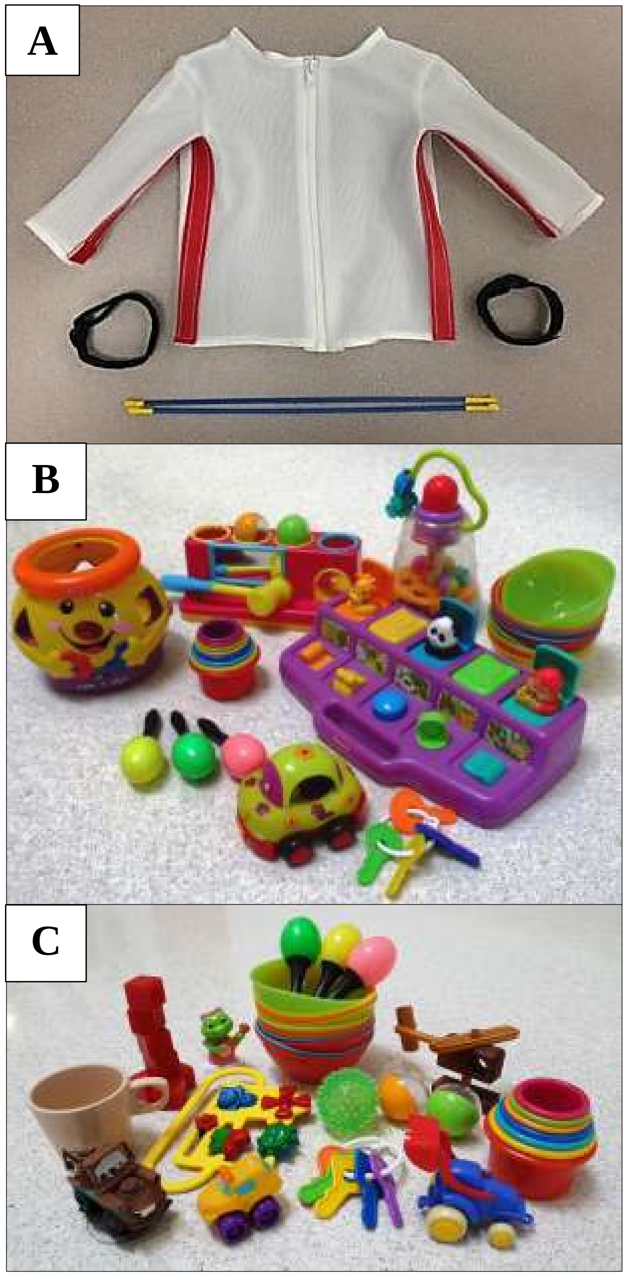
Figure 1.



doi: 10.1002/ajmg.c.31719

Figure 2.

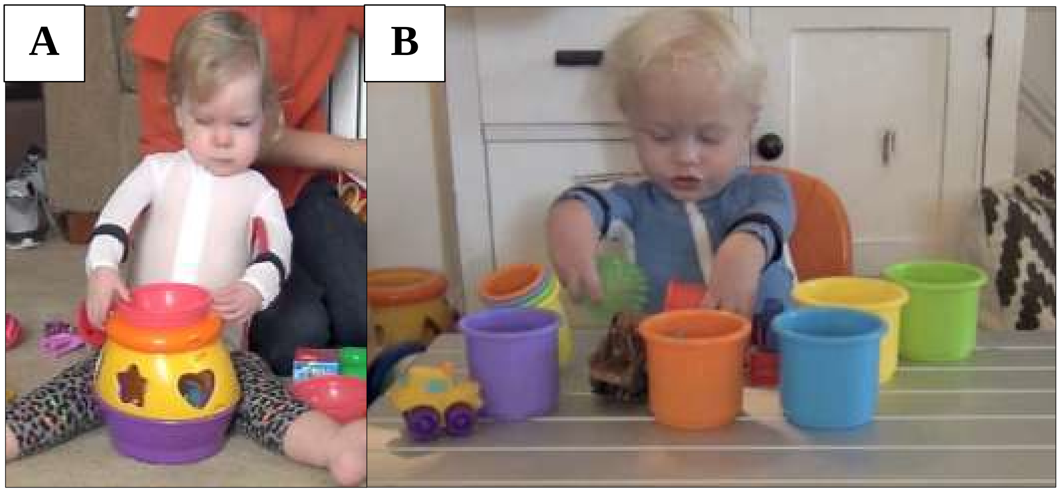


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Figure 3.

Behaviors	**FLOOR**			**SURFACE**		
	B	I	PI	B	I	PI
Unimanual contact						
Bimanual contact						
Supported contact						
Suspended contact						
Unimanual toy manipulation						
Bimanual toy manipulation						
Looking at the toy(s)						
Looking during unimanual contact						
Looking during bimanual contact						
Looking during supported contact						
Looking during suspended contact						
Looking during unimanual toy manipulation						
Looking during bimanual toy manipulation						
Bouts of exploration (intensity)						
Time performing single behaviors						
Time performing combined behaviors						
Variability of single behaviors						
Variability of combined behaviors						
Either hand at the head level						
Either hand at the chest level						
Either hand at the hip level						
Arm flings to reach the toy						
Trunk flings to reach the toy						

Figure 4.

	FLOOR		**SURFACE**	
Behaviors	B to I	B to PI	B to I	B to PI
Unimanual contact				
Bimanual contact				
Supported contact				
Suspended contact				
Unimanual toy manipulation				
Bimanual toy manipulation				
Looking at the toy(s)				
Looking during unimanual contact				
Looking during bimanual contact				
Looking during supported contact				
Looking during suspended contact				
Looking during unimanual toy manipulation				
Looking during bimanual toy manipulation				
Bouts of exploration (intensity)				
Time performing single behaviors				
Time performing combined behaviors				
Variability of single behaviors				
Variability of combined behaviors				
Either hand at the head level				
Either hand at the chest level				
Either hand at the hip level	NEG	NEG		
Arm flings to reach the toy		NEG		
Trunk flings to reach the toy				

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Supplementary Materials

Table S1. Statistical parameters from HLM (with Cohen's *d* effect sizes, *d*=0.2 small, *d* =0.5 medium, *d*=0.8 large) for the ***assistive effects*** of the Playskin on the outcome variables during the FLOOR and SURFACE assessments; assistive effects represent an improvement in function within study phases while wearing the Playskin; OFF = Playskin OFF condition; OFF/ON = difference between Playskin OFF and ON conditions; statistically significant *p* values in the comparison variable OFF/ON are marked in bold

Outcome Variables		FLOOR	SURFACE
Unimanual contact			
	Baseline	*OFF*: β = 36.52, *t*(16) = 7.92, *SE* = 4.61, *p* < .001 *OFF/ON*: β = 0.80, *t*(65) = 0.17, *SE* = 4.75, *p* = .866, *d* = 0.04	*OFF*: β = 30.83, *t*(16) = 9.62, *SE* = 3.21, *p* < .001 *OFF/ON*: β = 11.79, *t*(57) = 2.48, *SE* = 4.74, ***p* = .016**, *d* = 0.66
	Intervention	*OFF*: β = 39.23, *t*(16) = 9.92, *SE* = 3.95, *p* < .001 *OFF/ON*: β = 3.96, *t*(16) = 1.12, *SE* = 3.54, *p* = .280, *d* = 0.56	*OFF*: β = 38.50, *t*(16) = 10.61, *SE* = 3.63, *p* < .001 *OFF/ON*: β = 6.23, *t*(16) = 2.60, *SE* = 2.39, ***p* = .019**, *d* = 1.30
	Post-Intervention	*OFF*: β = 49.45, *t*(10) = 9.70, *SE* = 5.10, *p* < .001 *OFF/ON*: β = -5.82, *t*(10) = -1.27, *SE* = 4.57, *p* = .232, *d* = 0.80	*OFF*: β = 46.78, *t*(10) = 9.51, *SE* = 4.92, *p* < .001 *OFF/ON*: β = 0.46, *t*(73) = 0.16, *SE* = 2.83, *p* = .871, *d* = 0.04
Bimanual contact			
	Baseline	*OFF*: β = 18.05, *t*(16) = 4.63, *SE* = 3.90, *p* < .001 *OFF/ON*: β = 9.27, *t*(65) = 1.93, *SE* = 4.81, *p* = .059, *d* = 0.48	*OFF*: β = 19.83, *t*(16) = 3.82, *SE* = 5.19, *p* = .002 *OFF/ON*: β = 4.11, *t*(16) = 0.57, *SE* = 7.16, *p* = .574, *d* = 0.29
	Intervention	*OFF*: β = 24.30, *t*(16) = 5.79, *SE* = 4.20, *p* < .001 *OFF/ON*: β = 5.05, *t*(257) = 2.12, *SE* = 2.38, ***p* = .035**, *d* = 0.26	*OFF*: β = 23.82, *t*(16) = 6.00, *SE* = 3.97, *p* < .001 *OFF/ON*: β = 1.18, *t*(257) = 0.56, *SE* = 2.10, *p* = .575, *d* = 0.07
	Post-Intervention	*OFF*: β = 27.98, *t*(10) = 5.43, *SE* = 5.16, *p* < .001 *OFF/ON*: β = 6.36, *t*(74) = 1.58, *SE* = 4.02, *p* = .118, *d* = 0.37	*OFF*: β = 30.97, *t*(10) = 4.69, *SE* = 6.60, *p* < .001 *OFF/ON*: β = -2.28, *t*(73) = -0.63, *SE* = 3.63, *p* = .532, *d* = 0.15
Supported contact			
	Baseline	*OFF*: β = 51.12, *t*(16) = 7.56, *SE* = 6.76, *p* < .001 *OFF/ON*: β = 2.95, *t*(65) = 0.60, *SE* = 4.89, *p* = .548, *d* = 0.15	*OFF*: β = 46.65, *t*(16) = 6.75, *SE* = 6.91, *p* < .001 *OFF/ON*: β = 17.26, *t*(16) = 2.83, *SE* = 6.09, ***p* = .012**, *d* = 1.42
	Intervention	*OFF*: β = 58.05, *t*(16) = 10.46, *SE* = 5.55, *p* < .001 *OFF/ON*: β = 5.88, *t*(16) = 1.42, *SE* = 4.13, *p* = .174, *d* = 0.71	*OFF*: β = 57.62, *t*(16) = 13.41, *SE* = 4.30, *p* < .001 *OFF/ON*: β = 3.92, *t*(257) = 1.85, *SE* = 2.11, *p* = .065, *d* = 0.23
	Post-Intervention	*OFF*: β = 71.24, *t*(10) = 22.36, *SE* = 3.19, *p* < .001 *OFF/ON*: β = -1.35, *t*(74) = -0.47, *SE* = 2.84, *p* = .637, *d* = 0.11	*OFF*: β = 70.00, *t*(10) = 18.24, *SE* = 3.84, *p* < .001 *OFF/ON*: β = -4.09, *t*(73) = -1.34, *SE* = 3.05, *p* = .184, *d* = 0.31
Suspended contact			
	Baseline	*OFF*: β = 4.64, *t*(16) = 2.74, *SE* = 1.70, *p* = .015 *OFF/ON*: β = 6.63, *t*(65) = 2.63, *SE* = 2.52, ***p* = .011**, *d* = 0.65	*OFF*: β = 6.71, *t*(16) = 2.63, *SE* = 2.55, *p* = .018 *OFF/ON*: β = 0.08, *t*(57) = 0.03, *SE* = 2.69, *p* = .976, *d* = 0.01
	Intervention	*OFF*: β = 6.83, *t*(16) = 3.58, *SE* = 1.90, *p* = .002 *OFF/ON*: β = 4.72, *t*(257) = 4.24, *SE* = 1.11, ***p* < .001**, *d* = 0.53	*OFF*: β = 7.55, *t*(16) = 3.61, *SE* = 2.09, *p* = .002 *OFF/ON*: β = 4.53, *t*(16) = 2.29, *SE* = 1.98, ***p* = .036**, *d* = 1.15
	Post-Intervention	*OFF: β = 7.89, t(10) = 3.11, SE = 2.54, p = .011* *OFF/ON: β = 3.36, t(10) = 1.38, SE = 2.43, p = .198, d = 0.87*	*OFF: β = 11.28, t(10) = 2.94, SE = 3.84, p = .015* *OFF/ON: β = 2.80, t(73) = 1.45, SE = 1.95, p = .155, d = 0.34*

Unimanual toy manipulation			
	Baseline	*OFF*: $\beta = 9.72$, $t(16) = 3.42$, $SE = 2.84$, $p = .004$ *OFF/ON*: $\beta = 9.65$, $t(65) = 3.09$, $SE = 3.12$, **$p = .003$**, $d = 0.77$	*OFF*: $\beta = 3.20$, $t(16) = 2.65$, $SE = 1.21$, $p = .017$ *OFF/ON*: $\beta = -0.38$, $t(57) = -0.24$, $SE = 1.56$, $p = .808$, $d = 0.06$
	Intervention	*OFF*: $\beta = 14.32$, $t(16) = 4.94$, $SE = 2.90$, $p < .001$ *OFF/ON*: $\beta = 2.44$, $t(257) = 1.53$, $SE = 1.60$, $p = .128$, $d = 0.19$	*OFF*: $\beta = 6.23$, $t(16) = 3.90$, $SE = 1.60$, $p = .001$ *OFF/ON*: $\beta = 3.18$, $t(257) = 2.26$, $SE = 1.41$, **$p = .025$**, $d = 0.28$
	Post-Intervention	*OFF*: $\beta = 18.42$, $t(10) = 4.46$, $SE = 4.13$, $p < .001$ *OFF/ON*: $\beta = 1.45$, $t(10) = 0.46$, $SE = 3.26$, $p = .666$, $d = 0.29$	*OFF*: $\beta = 10.32$, $t(10) = 4.08$, $SE = 2.53$, $p = .002$ *OFF/ON*: $\beta = -0.31$, $t(73) = -0.11$, $SE = 2.83$, $p = .913$, $d = 0.03$
Bimanual toy manipulation			
	Baseline	*OFF*: $\beta = 0.76$, $t(81) = 0.92$, $SE = 0.82$, $p = .362$ *OFF/ON*: $\beta = 4.00$, $t(81) = 2.61$, $SE = 1.53$, **$p = .011$**, $d = 0.58$	*OFF*: $\beta = 0.02$, $t(73) = 0.19$, $SE = 0.12$, $p = .849$ *OFF/ON*: $\beta = 0.50$, $t(73) = 2.07$, $SE = 0.24$, **$p = .042$**, $d = 0.48$
	Intervention	*OFF*: $\beta = 1.10$, $t(257) = 2.92$, $SE = 0.38$, $p = .004$ *OFF/ON*: $\beta = 0.97$, $t(16) = 1.23$, $SE = 0.79$, $p = .237$, $d = 0.62$	*OFF*: $\beta = 0.88$, $t(16) = 1.71$, $SE = 0.51$, $p = .107$ *OFF/ON*: $\beta = 0.02$, $t(257) = 0.05$, $SE = 0.40$, $p = .962$, $d = 0.01$
	Post-Intervention	*OFF*: $\beta = 0.79$, $t(74) = 1.81$, $SE = 0.44$, $p = .074$ *OFF/ON*: $\beta = 1.62$, $t(10) = 1.16$, $SE = 1.40$, $p = .275$, $d = 0.73$	*OFF*: $\beta = 0.96$, $t(10) = 1.97$, $SE = 0.49$, $p = .077$ *OFF/ON*: $\beta = -0.01$, $t(73) = -0.01$, $SE = 0.56$, $p = .991$, $d = 0.002$
Looking at the toy(s)			
	Baseline	*OFF*: $\beta = 74.05$, $t(16) = 18.25$, $SE = 4.06$, $p < .001$ *OFF/ON*: $\beta = 0.90$, $t(65) = 0.26$, $SE = 3.45$, $p = .795$, $d = 0.06$	*OFF*: $\beta = 74.90$, $t(16) = 20.47$, $SE = 3.66$, $p < .001$ *OFF/ON*: $\beta = 1.38$, $t(57) = 0.40$, $SE = 3.47$, $p = .692$, $d = 0.11$
	Intervention	*OFF*: $\beta = 76.99$, $t(16) = 33.41$, $SE = 2.30$, $p < .001$ *OFF/ON*: $\beta = 1.88$, $t(257) = 1.04$, $SE = 1.81$, $p = .301$, $d = 0.13$	*OFF*: $\beta = 78.01$, $t(16) = 34.40$, $SE = 2.27$, $p < .001$ *OFF/ON*: $\beta = 1.47$, $t(257) = 0.72$, $SE = 2.05$, $p = .473$, $d = 0.09$
	Post-Intervention	*OFF*: $\beta = 80.88$, $t(10) = 26.40$, $SE = 3.06$, $p < .001$ *OFF/ON*: $\beta = 4.10$, $t(74) = 1.75$, $SE = 2.34$, $p = .084$, $d = 0.41$	*OFF*: $\beta = 83.03$, $t(10) = 33.63$, $SE = 2.47$, $p < .001$ *OFF/ON*: $\beta = 3.28$, $t(73) = 2.66$, $SE = 1.23$, **$p = .010$**, $d = 0.62$
Looking during unimanual contact			
	Baseline	*OFF*: $\beta = 30.37$, $t(16) = 7.31$, $SE = 4.16$, $p < .001$ *OFF/ON*: $\beta = -2.02$, $t(65) = -0.50$, $SE = 4.01$, $p = .617$, $d = 0.12$	*OFF*: $\beta = 25.06$, $t(16) = 7.37$, $SE = 3.40$, $p < .001$ *OFF/ON*: $\beta = 9.72$, $t(16) = 2.31$, $SE = 4.20$, **$p = .034$**, $d = 1.16$
	Intervention	*OFF*: $\beta = 32.80$, $t(16) = 9.44$, $SE = 3.47$, $p < .001$ *OFF/ON*: $\beta = 2.95$, $t(16) = 1.01$, $SE = 2.91$, $p = .326$, $d = 0.51$	*OFF*: $\beta = 33.01$, $t(16) = 10.72$, $SE = 3.08$, $p < .001$ *OFF/ON*: $\beta = 3.20$, $t(257) = 1.86$, $SE = 1.73$, $p = .065$, $d = 0.23$
	Post-Intervention	*OFF*: $\beta = 41.54$, $t(10) = 10.21$, $SE = 4.07$, $p < .001$ *OFF/ON*: $\beta = -4.10$, $t(74) = -1.27$, $SE = 3.24$, $p = .210$, $d = 0.30$	*OFF*: $\beta = 40.66$, $t(10) = 7.86$, $SE = 5.17$, $p < .001$ *OFF/ON*: $\beta = 1.42$, $t(73) = 0.52$, $SE = 2.75$, $p = .607$, $d = 0.12$
Looking during bimanual contact			
	Baseline	*OFF*: $\beta = 14.61$, $t(16) = 4.36$, $SE = 3.35$, $p < .001$ *OFF/ON*: $\beta = 8.35$, $t(65) = 2.12$, $SE = 3.94$, **$p = .038$**, $d = 0.53$	*OFF*: $\beta = 16.53$, $t(16) = 3.80$, $SE = 4.35$, $p = .002$ *OFF/ON*: $\beta = 4.29$, $t(16) = 0.75$, $SE = 5.74$, $p = .466$, $d = 0.38$
	Intervention	*OFF*: $\beta = 19.46$, $t(16) = 5.17$, $SE = 3.76$, $p < .001$ *OFF/ON*: $\beta = 5.30$, $t(257) = 2.68$, $SE = 1.98$, **$p = .008$**, $d = 0.33$	*OFF*: $\beta = 19.00$, $t(16) = 5.62$, $SE = 3.38$, $p < .001$ *OFF/ON*: $\beta = 2.08$, $t(257) = 1.20$, $SE = 1.74$, $p = .232$, $d = 0.15$
	Post-Intervention	*OFF*: $\beta = 22.98$, $t(10) = 5.20$, $SE = 4.42$, $p < .001$ *OFF/ON*: $\beta = 7.39$, $t(10) = 1.52$, $SE = 4.88$, $p = .160$, $d = 0.96$	*OFF*: $\beta = 24.43$, $t(10) = 4.86$, $SE = 5.03$, $p < .001$ *OFF/ON*: $\beta = -0.26$, $t(73) = -0.09$, $SE = 2.95$, $p = .930$, $d = 0.02$

Looking during supported contact			
	Baseline	*OFF*: β = 42.25, t(16) = 7.00, *SE* = 6.03, p < .001 *OFF/ON*: β = 2.26, t(65) = 0.57, *SE* = 3.97, p = .570, d = 0.14	*OFF*: β = 38.40, t(16) = 6.43, *SE* = 5.97, p < .001 *OFF/ON*: β = 11.43, t(57) = 3.05, *SE* = 3.74, **p = .003**, d = 0.81
	Intervention	*OFF*: β = 48.23, t(16) = 9.74, *SE* = 4.95, p < .001 *OFF/ON*: β = 5.37, t(16) = 1.80, *SE* = 2.99, p = .091, d = 0.90	*OFF*: β = 47.99, t(16) = 11.66, *SE* = 4.12, p < .001 *OFF/ON*: β = 2.49, t(257) = 1.20, *SE* = 2.08, p = .231, d = 0.15
	Post-Intervention	*OFF*: β = 60.39, t(10) = 14.49, *SE* = 4.17, p < .001 *OFF/ON*: β = 0.23, t(74) = 0.08, *SE* = 2.93, p = .939, d = 0.02	*OFF*: β = 58.45, t(10) = 16.73, *SE* = 3.49, p < .001 *OFF/ON*: β = -0.55, t(73) = -0.20, *SE* = 2.77, p = .842, d = 0.05
Looking during suspended contact			
	Baseline	*OFF*: β = 3.66, t(16) = 2.97, *SE* = 1.23, p = .009 *OFF/ON*: β = 3.59, t(65) = 2.33, *SE* = 1.54, **p = .023**, d = 0.58	*OFF*: β = 5.83, t(16) = 2.57, *SE* = 2.27, p = .020 *OFF/ON*: β = -0.12, t(57) = -0.05, *SE* = 2.59, p = .963, d = 0.01
	Intervention	*OFF*: β = 5.29, t(16) = 3.61, *SE* = 1.46, p = .002 *OFF/ON*: β = 4.01, t(16) = 3.32, *SE* = 1.21, **p = .004**, d = 1.66	*OFF*: β = 6.19, t(16) = 3.61, *SE* = 1.71, p = .002 *OFF/ON*: β = 4.09, t(16) = 2.54, *SE* = 1.61, **p = .022**, d = 1.27
	Post-Intervention	*OFF*: β = 5.83, t(10) = 3.22, *SE* = 1.81, p = .009 *OFF/ON*: β = 3.89, t(10) = 1.91, *SE* = 2.04, p = .085, d = 1.21	*OFF*: β = 9.55, t(10) = 2.97, *SE* = 3.21, p =.014 *OFF/ON*: β = 2.23, t(73) = 1.37, *SE* = 1.63, p = .174, d = 0.32
Looking during unimanual toy manipulation			
	Baseline	*OFF*: β = 8.91, t(16) = 3.27, *SE* = 2.72, p = .005 *OFF/ON*: β = 8.02, t(65) = 2.81, *SE* = 2.85, **p = .006**, d = 0.70	*OFF*: β = 2.96, t(16) = 2.65, *SE* = 1.12, p = .018 *OFF/ON*: β = -0.61, t(57) = -0.43, *SE* = 1.42, p = .671, d = 0.11
	Intervention	*OFF*: β = 12.85, t(16) = 4.68, *SE* =2.75, p < .001 *OFF/ON*: β = 1.86, t(257) = 1.27, *SE* = 1.46, p = .205, d = 0.16	*OFF*: β = 5.76, t(16) = 3.92, *SE* = 1.47, p = .001 *OFF/ON*: β = 2.65, t(257) = 2.04, *SE* = 1.30, **p = .043**, d = 0.25
	Post-Intervention	*OFF*: β = 16.93, t(10) = 4.37, *SE* = 3.87, p < .001 *OFF/ON*: β = 1.31, t(10) = 0.46, *SE* = 2.88, p = .658, d = 0.29	*OFF*: β = 9.43, t(10) = 3.82, *SE* = 2.47, p = .003 *OFF/ON*: β = -0.005, t(73) = -0.002, *SE* = 2.67, p = .999, d = 0.0005
Looking during bimanual toy manipulation			
	Baseline	*OFF*: β = 0.53, t(81) = 0.67, *SE* = 0.79, p = .506 *OFF/ON*: β = 3.98, t(81) = 2.71, *SE* = 1.47, **p = .008**, d = 0.60	*OFF*: β = 0.01, t(57) = 1.14, *SE* = 0.09, p = .893 *OFF/ON*: β = 0.52, t(16) = 1.17, *SE* = 0.44, p = .258, d = 0.59
	Intervention	*OFF*: β = 0.73, t(16) = 1.45, *SE* = 0.50, p = .165 *OFF/ON*: β = 1.27, t(257) = 2.53, *SE* = 050, **p = .012**, d = 0.32	*OFF*: β = 0.78, t(16) = 1.64, *SE* = 0.48, p = .121 *OFF/ON*: β = 0.08, t(257) = 0.21, *SE* = 0.37, p = .834, d = 0.03
	Post-Intervention	*OFF*: β = 0.63, t(10) = 0.84, *SE* = 0.75, p = .423 *OFF/ON*: β = 1.61, t(74) = 2.31, *SE* = 0.70, **p = .024**, d = 0.54	*OFF*: β = 0.72, t(83) = 2.09, *SE* = 0.35, p = .040 *OFF/ON*: β = 0.07, t(83) = 0.14, *SE* = 0.49, p = .886, d = 0.03
Bouts of exploration (intensity)			
	Baseline	*OFF*: β = 23.47, t(16) = 6.49, *SE* = 3.61, p < .001 *OFF/ON*: β = 10.01, t(65) = 3.14, *SE* = 3.19, **p = .003**, d = 0.78	*OFF*: β = 20.72, t(16) = 6.94, *SE* = 2.99, p < .001 *OFF/ON*: β = 2.52, t(57) = 0.93, *SE* = 2.71, p = .357, d = 0.25
	Intervention	*OFF*: β = 26.23, t(16) = 7.88, *SE* =3.33, p < .001 *OFF/ON*: β = 5.63, t(16) = 2.39, *SE* = 2.36, **p = .030**, d = 1.20	*OFF*: β = 22.78, t(16) = 8.31, *SE* = 2.74, p < .001 *OFF/ON*: β = 6.28, t(257) = 5.56, *SE* = 1.13, **p < .001**, d = 0.69
	Post-Intervention	*OFF*: β = 33.55, t(10) = 8.52, *SE* = 3.94, p < .001 *OFF/ON*: β = 6.79, t(10) = 1.44, *SE* = 4.72, p = .181, d = 0.91	*OFF*: β = 28.92, t(10) = 6.67, *SE* = 4.33, p < .001 *OFF/ON*: β = 4.23, t(73) = 1.79, *SE* = 2.37, p = .078, d = 0.42

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Time performing single behaviors			
	Baseline	OFF: $\beta = 33.73$, $t(16) = 8.17$, $SE = 4.13$, $p < .001$ OFF/ON: $\beta = -3.10$, $t(65) = -0.78$, $SE = 3.96$, $p = .437$, $d = 0.19$	OFF: $\beta = 38.38$, $t(16) = 7.43$, $SE = 5.17$, $p < .001$ OFF/ON: $\beta = -5.29$, $t(16) = -1.13$, $SE = 4.67$, $p = .274$, $d = 0.57$
	Intervention	OFF: $\beta = 28.25$, $t(16) = 7.09$, $SE = 3.98$, $p < .001$ OFF/ON: $\beta = -5.76$, $t(16) = -2.89$, $SE = 1.99$, $p = .011$, $d = 1.45$	OFF: $\beta = 30.16$, $t(16) = 8.58$, $SE = 3.51$, $p < .001$ OFF/ON: $\beta = -1.55$, $t(257) = -1.03$, $SE = 1.51$, $p = .305$, $d = 0.13$
	Post-Intervention	OFF: $\beta = 18.94$, $t(10) = 6.63$, $SE = 2.86$, $p < .001$ OFF/ON: $\beta = -1.21$, $t(74) = -0.57$, $SE = 2.15$, $p = .573$, $d = 0.13$	OFF: $\beta = 23.28$, $t(10) = 7.43$, $SE = 3.13$, $p < .001$ OFF/ON: $\beta = 0.71$, $t(73) = 0.32$, $SE = 2.23$, $p = .750$, $d = 0.07$
Time performing combined behaviors			
	Baseline	OFF: $\beta = 49.05$, $t(16) = 7.01$, $SE = 6.99$, $p < .001$ OFF/ON: $\beta = 6.12$, $t(65) = 2.12$, $SE = 2.89$, $p = .038$, $d = 0.53$	OFF: $\beta = 45.09$, $t(16) = 5.83$, $SE = 7.74$, $p < .001$ OFF/ON: $\beta = 13.06$, $t(16) = 2.30$, $SE = 5.68$, $p = .035$, $d = 1.15$
	Intervention	OFF: $\beta = 57.94$, $t(16) = 9.67$, $SE = 5.99$, $p < .001$ OFF/ON: $\beta =8.99$, $t(16) = 2.85$, $SE = 3.16$, $p = .012$, $d = 1.43$	OFF: $\beta = 57.03$, $t(16) = 10.91$, $SE = 5.22$, $p < .001$ OFF/ON: $\beta = 4.96$, $t(257) = 2.47$, $SE = 2.01$, $p = .014$, $d = 0.31$
	Post-Intervention	OFF: $\beta = 71.66$, $t(10) = 19.89$, $SE = 3.60$, $p < .001$ OFF/ON: $\beta = 2.74$, $t(74) = 0.93$, $SE = 2.93$, $p = .353$, $d = 0.22$	OFF: $\beta = 72.45$, $t(10) = 19.05$, $SE = 3.80$, $p < .001$ OFF/ON: $\beta = -0.36$, $t(73) = -0.13$, $SE = 2.74$, $p = .895$, $d = 0.03$
Variability of single behaviors			
	Baseline	OFF: $\beta = 41.23$, $t(16) = 12.63$, $SE = 3.26$, $p < .001$ OFF/ON: $\beta = 7.15$, $t(65) = 3.99$, $SE = 1.79$, $p < .001$, $d = 0.99$	OFF: $\beta = 35.68$, $t(16) = 14.82$, $SE = 2.41$, $p < .001$ OFF/ON: $\beta = 0.28$, $t(57) = 0.15$, $SE = 1.95$, $p = .885$, $d = 0.04$
	Intervention	OFF: $\beta = 44.05$, $t(16) = 14.72$, $SE = 2.99$, $p < .001$ OFF/ON: $\beta =4.88$, $t(16) =3.85$, $SE = 1.27$, $p = .001$, $d = 1.93$	OFF: $\beta = 39.30$, $t(16) = 19.96$, $SE = 1.97$, $p < .001$ OFF/ON: $\beta = 0.38$, $t(16) = 0.36$, $SE =1.07$, $p = .725$, $d = 0.18$
	Post-Intervention	OFF: $\beta = 48.73$, $t(10) = 17.72$, $SE = 2.75$, $p < .001$ OFF/ON: $\beta = 3.17$, $t(74) = 2.03$, $SE = 1.56$, $p = .046$, $d = 0.47$	OFF: $\beta = 41.57$, $t(10) = 19.72$, $SE =2.11$, $p < .001$ OFF/ON: $\beta = 0.26$, $t(73) = 0.16$, $SE = 1.61$, $p = .870$, $d = 0.04$
Variability of combined behaviors			
	Baseline	OFF: $\beta = 0.03$, $t(16) = 4.18$, $SE = 0.01$, $p < .001$ OFF/ON: $\beta = 0.03$, $t(16) = 2.88$, $SE = 0.01$, $p = .011$, $d = 1.44$	OFF: $\beta = 0.02$, $t(16) = 4.72$, $SE = 0.005$, $p < .001$ OFF/ON: $\beta = 0.004$, $t(16) = 0.96$, $SE = 0.004$, $p = .350$, $d = 0.48$
	Intervention	OFF: $\beta = 0.04$, $t(16) = 5.82$, $SE = 0.01$, $p < .001$ OFF/ON: $\beta = 0.01$, $t(16) = 2.43$, $SE = 0.01$, $p = .027$, $d = 1.22$	OFF: $\beta = 0.03$, $t(16) = 5.79$, $SE = 0.004$, $p < .001$ OFF/ON: $\beta = 0.01$, $t(16) = 2.57$, $SE = 0.002$, $p = .021$, $d = 1.29$
	Post-Intervention	OFF: $\beta = 0.05$, $t(10) = 5.51$, $SE = 0.01$, $p < .001$ OFF/ON: $\beta = 0.02$, $t(74) = 3.87$, $SE = 0.01$, $p < .001$, $d = 0.90$	OFF: $\beta = 0.03$, $t(10) = 4.49$, $SE = 0.01$, $p = .001$ OFF/ON: $\beta = 0.01$, $t(73) = 2.00$, $SE = 0.004$, $p = .049$, $d = 0.47$
Either hand at the head level			
	Baseline	OFF: $\beta = 0.24$, $t(16) = 1.21$, $SE = 0.20$, $p = .245$ OFF/ON: $\beta = 0.54$, $t(65) = 2.12$, $SE = 0.25$, $p = .038$, $d = 0.53$	OFF: $\beta = 0.59$, $t(57) = 1.71$, $SE = 0.34$, $p = .091$ OFF/ON: $\beta = 0.98$, $t(16) = 0.79$, $SE = 1.24$, $p = .441$, $d = 0.40$
	Intervention	OFF: $\beta = 0.40$, $t(16) = 1.76$, $SE = 0.23$, $p = .098$ OFF/ON: $\beta = 0.27$, $t(257) = 1.25$, $SE = 0.21$, $p = .212$, $d = 0.16$	OFF: $\beta = 0.33$, $t(16) = 0.81$, $SE = 0.41$, $p = .430$ OFF/ON: $\beta = 0.65$, $t(257) = 1.65$, $SE = 0.39$, $p = .100$, $d = 0.21$
	Post-Intervention	OFF: $\beta = 0.66$, $t(10) = 2.36$, $SE = 0.28$, $p = .040$ OFF/ON: $\beta =-0.53$, $t(74) = -1.65$, $SE = 0.32$, $p = .103$, $d = 0.38$	OFF: $\beta = 0.82$, $t(10) = 1.41$, $SE = 0.59$, $p = .190$ OFF/ON: $\beta = -0.01$, $t(73) = -0.02$, $SE = 0.36$, $p = .988$, $d = 0.005$

Either hand at the chest level			
	Baseline	*OFF*: β = 15.53, $t(16)$ = 3.78, *SE* = 4.11, p = .002 *OFF/ON*: β = 34.43, $t(65)$ = 7.11, *SE* = 4.84, **p < .001**, d = 1.76	*OFF: β = 89.81, t(16) = 19.66, SE = 4.57, p < .001* *OFF/ON: β = 6.44, t(57) = 1.03, SE = 6.27, p = .309, d = 0.27*
	Intervention	*OFF*: β = 16.94, $t(16)$ = 4.55, *SE* = 3.73, p < .001 *OFF/ON*: β = 17.52, $t(16)$ = 3.44, *SE* = 5.09, **p = .003**, d = 1.72	*OFF: β = 91.10, t(16) = 33.36, SE = 2.73, p < .001* *OFF/ON: β = 3.53, t(257) = 2.09, SE = 1.69, p = .037, d = 0.26*
	Post-Intervention	*OFF*: β = 23.73, $t(10)$ = 4.32, *SE* = 5.50, p = .002 *OFF/ON*: β = 13.37, $t(10)$ = 1.78, *SE* =7.51, p = .105, d = 1.13	*OFF: β = 89.62, t(10) = 17.27, SE = 5.19, p < .001* *OFF/ON: β = -0.05, t(73) = -0.01, SE = 5.10, p = .992, d = 0.002*
Either hand at the hip level			
	Baseline	*OFF*: β = 97.14, $t(81)$ = 50.19, *SE* = 1.94, p < .001 *OFF/ON*: β = -24.51, $t(81)$ = -6.81, *SE* = 3.60, **p < .001**, d = 1.51	*OFF: β = 13.35, t(16) = 3.53, SE = 3.79, p = .003* *OFF/ON: β = -10.00, t(57) = -2.15, SE = 4.66, p = .036, d = 0.57*
	Intervention	*OFF*: β = 95.32, $t(16)$ = 48.93, *SE* = 1.95, p < .001 *OFF/ON*: β = -14.69, $t(16)$ = -2.37, *SE* = 6.20, **p = .031**, d = 1.19	*OFF: β = 25.35, t(16) = 6.48, SE = 3.91, p < .001* *OFF/ON: β =-11.95, t(257) = -3.77, SE = 3.17, p < .001, d = 0.47*
	Post-Intervention	*OFF*: β = 90.95, $t(74)$ = 35.01, *SE* = 2.60, p < .001 *OFF/ON*: β = -10.39, $t(10)$ = -1.47, *SE* = 7.09, p = .173, d = 0.93	*OFF: β = 21.95, t(10) = 3.75, SE = 5.86, p = .004* *OFF/ON: β = -4.39, t(73) = -0.83, SE = 5.27, p = .408, d = 0.19*
Arm flings to reach the toy			
	Baseline	*OFF*: β = 0.37, $t(16)$ = 2.04, *SE* = 0.18, p = .059 *OFF/ON*: β = -0.54, $t(65)$ = -2.02, *SE* = 0.27, **p = .048**, d = 0.50	*OFF: β = 0.02, t(73) = 1.16, SE = 0.02, p = .249* *OFF/ON: β = -0.02, t(73) = -0.60, SE = 0.04, p = .550, d = 0.14*
	Intervention	*OFF*: β = 0.45, $t(16)$ = 1.40, *SE* = 0.32, p = .180 *OFF/ON*: β = -0.32, $t(16)$ = -1.02, *SE* = 0.32, p = .322, d = 0.51	*OFF: β = 2.22, t(16) = 3.15, SE = 0.70, p = .006* *OFF/ON: β = -2.18, t(257) = -4.39, SE = 0.50, p < .001, d = 0.55*
	Post-Intervention	*OFF*: β = 0.51, $t(10)$ = 2.07, *SE* = 0.25, p = .065 *OFF/ON*: β = -0.51, $t(74)$ = -2.26, *SE* = 0.23, **p = .027**, d = 0.53	*OFF: β = 2.13, t(10) = 2.27, SE = 0.94, p = .047* *OFF/ON: β = -2.05, t(73) = -2.32, SE = 0.88, p = .023, d = 0.54*
Trunk flings to reach the toy			
	Baseline	*OFF*: β = 1.08, $t(16)$ = 2.20, *SE* = 0.49, p = .043 *OFF/ON*: β = -1.46, $t(65)$ = -2.09, *SE* = 0.70, **p = .041**, d = 0.52	*OFF: β = 0.10, t(73) = 1.33, SE = 0.08, p = .189* *OFF/ON: β = -0.10, t(73) = -0.68, SE = 0.15, p = .496, d = 0.16*
	Intervention	*OFF*: β = 0.79, $t(16)$ = 3.68, *SE* = 0.21, p = .002 *OFF/ON*: β = -0.68, $t(257)$ = -2.83, *SE* = 0.24, **p = .005**, d = 0.35	*OFF: β = 0.80, t(16) = 1.99, SE = 0.40, p = .064* *OFF/ON: β = -0.87, t(257) = -2.29, SE = 0.38, p = .023, d = 0.29*
	Post-Intervention	*OFF*: β = 0.42, $t(10)$ = 1.75, *SE* = 0.24, p = .111 *OFF/ON*: β = -0.42, $t(74)$ = -1.53, *SE* = 0.28, p = .129, d = 0.36	NA

Table S2. Statistical parameters from HLM (with Cohen's *d* effect sizes, *d*=0.2 small, *d* =0.5 medium, *d*=0.8 large) for the ***rehabilitative effects*** of the Playskin on the outcome variables during the FLOOR and SURFACE assessments; rehabilitative effects represent an improvement in time children independently perform behaviors when not wearing the Playskin; B = Baseline; B/I = change from Baseline to Intervention; B/PI = change from Baseline to Post-Intervention; statistically significant *p* values in the comparison variables B/I and B/PI are marked in bold

Outcome Variables	FLOOR	SURFACE
Unimanual contact	*B*: β = 36.24, *t*(16) = 7.58, *SE* = 4.78, *p* < .001 *B/I*: β = 2.90, *t*(16) = 0.79, *SE* = 3.68, *p* = .443, *d* = 0.40 *B/PI*: β = 8.63, *t*(205) = 2.37, *SE* = 3.64, ***p* = .019**, *d* = 0.33	*B*: β = 31.19, *t*(16) = 8.59, *SE* = 3.63, *p* < .001 *B/I*: β = 7.74, *t*(201) = 3.00, *SE* = 2.58, ***p* = .003**, *d* = 0.42 *B/PI*: β = 12.94, *t*(16) = 2.69, *SE* = 4.82, ***p* = .016**, *d* = 1.35
Bimanual contact	*B*: β = 17.91, *t*(16) = 4.46, *SE* = 4.01, *p* < .001 *B/I*: β = 6.61, *t*(16) = 1.65, *SE* = 4.01, *p* = .119, *d* = 0.83 *B/PI*: β = 7.53, *t*(16) = 1.54, *SE* = 4.89, *p* = .143, *d* = 0.77	*B*: β = 19.50, *t*(16) = 4.19, *SE* = 4.66, *p* < .001 *B/I*: β = 4.58, *t*(201) = 1.62, *SE* = 2.83, *p* = .107, *d* = 0.23 *B/PI*: β = 9.39, *t*(16) = 1.97, *SE* = 4.76, *p* = .066, *d* = 0.99
Supported contact	*B*: β = 50.50, *t*(16) = 8.32, *SE* = 6.07, *p* < .001 *B/I*: β = 7.93, *t*(16) = 2.10, *SE* = 3.78, *p* = .052, *d* = 1.05 *B/PI*: β = 13.51, *t*(205) = 3.48, *SE* = 3.88, ***p* < .001**, *d* = 0.49	*B*: β = 46.90, *t*(16) = 6.74, *SE* = 6.96, *p* < .001 *B/I*: β = 10.85, *t*(16) = 2.03, *SE* = 5.34, *p* = .059, *d* = 1.02 *B/PI*: β = 20.73, *t*(16) = 3.39, *SE* = 6.12, ***p* = .004**, *d* = 1.70
Suspended contact	*B*: β = 4.70, *t*(16) = 2.70, *SE* = 1.74, *p* = .016 *B/I*: β = 2.35, *t*(205) = 2.16, *SE* = 1.09, ***p* = .032**, *d* = 0.30 *B/PI*: β = 3.72, *t*(16) = 1.90, *SE* = 1.96, *p* = .076, *d* = 0.95	*B*: β = 6.64, *t*(16) = 2.64, *SE* = 2.52, *p* = .018 *B/I*: β = 1.57, *t*(201) = 1.20, *SE* = 1.31, *p* = .231, *d* = 0.17 *B/PI*: β = 4.60, *t*(16) = 1.37, *SE* = 3.34, *p* = .188, *d* = 0.69
Unimanual toy manipulation	*B*: β = 9.20, *t*(16) = 2.94, *SE* = 3.13, *p* = .010 *B/I*: β = 5.44, *t*(221) = 3.14, *SE* = 1.73, ***p* = .002**, *d* = 0.42 *B/PI*: β = 6.72, *t*(221) = 2.96, *SE* = 2.27, ***p* = .003**, *d* = 0.40	*B*: β = 3.35, *t*(16) = 1.82, *SE* = 1.84, *p* = .088 *B/I*: β = 2.96, *t*(217) = 1.91, *SE* = 1.55, *p* = .058, *d* = 0.26 *B/PI*: β = 6.37, *t*(217) = 3.16, *SE* = 2.02, ***p* = .002**, *d* = 0.43
Bimanual toy manipulation	*B*: β = 0.73, *t*(16) = 1.67, *SE* = 0.44, *p* = .114 *B/I*: β = 0.32, *t*(221) = 0.71, *SE* = 0.46, *p* = .479, *d* = 0.10 *B/PI*: β = -0.02, *t*(221) = -0.03, *SE* = 0.60, *p* = .980, *d* = 0.004	*B*: β =0.05, *t*(16) = 0.10, *SE* = 0.48, *p* = .919 *B/I*: β = 0.84, *t*(217) = 1.85, *SE* = 0.46, *p* = .065, *d* = 0.25 *B/PI*: β = 0.74, *t*(217) = 1.26, *SE* = 0.59, *p* = .210, *d* = 0.17
Looking at the toy(s)	*B*: β = 73.93, *t*(16) = 20.01, *SE* = 3.69, *p* < .001 *B/I*: β = 2.76, *t*(16) = 0.93, *SE* = 2.97, *p* = .366, *d* = 0.47 *B/PI*: β = 4.40, *t*(205) = 1.53, *SE* = 2.88, *p* = .128, *d* = 0.21	*B*: β = 75.50, *t*(16) = 27.84, *SE* = 2.71, *p* < .001 *B/I*: β = 2.85, *t*(217) = 1.12, *SE* = 2.54, *p* = .265, *d* = 0.15 *B/PI*: β = 6.73, *t*(217) = 2.04, *SE* = 3.29, ***p* = .042**, *d* = 0.28
Looking during unimanual contact	*B*: β = 30.08, *t*(16) = 7.09, *SE* = 4.24, *p* < .001 *B/I*: β = 2.79, *t*(16) = 0.84, *SE* = 3.35, *p* = .416, *d* = 0.42 *B/PI*: β = 7.90, *t*(205) = 2.42, *SE* = 3.27, ***p* = .016**, *d* = 0.34	*B*: β = 25.80, *t*(16) = 7.29, *SE* = 3.54, *p* < .001 *B/I*: β = 7.60, *t*(217) = 3.02, *SE* = 2.52, ***p* = .003**, *d* = 0.41 *B/PI*: β = 12.28, *t*(217) = 3.75, *SE* = 3.27, ***p* < .001**, *d* = 0.51
Looking during bimanual contact	*B*: β = 14.56, *t*(16) = 4.54, *SE* = 3.21, *p* < .001 *B/I*: β = 5.24, *t*(16) = 1.80, *SE* = 2.91, *p* = .091, *d* = 0.90 *B/PI*: β = 6.51, *t*(16) = 1.56, *SE* = 4.16, *p* = .138, *d* = 0.78	*B*: β = 16.63, *t*(16) = 4.32, *SE* = 3.85, *p* < .001 *B/I*: β = 2.66, *t*(201) = 1.21, *SE* = 2.21, *p* = .229, *d* = 0.17 *B/PI*: β = 6.62, *t*(16) = 1.78, *SE* = 3.72, *p* = .094, *d* = 0.89
Looking during supported contact	*B: β = 41.71, t(16) = 7.99, SE = 5.22, p < .001* *B/I: β = 7.26, t(221) = 2.71, SE = 2.68, p = .007, d = 0.36* *B/PI: β = 12.20, t(221) = 3.47, SE = 3.51, p < .001, d = 0.47*	*B: β = 39.37, t(16) = 7.97, SE = 4.94, p < .001* *B/I: β = 8.72, t(217) = 3.13, SE = 2.78, p = .002, d = 0.42* *B/PI: β = 15.28, t(217) = 4.23, SE = 3.62, p < .001, d = 0.57*

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Looking during suspended contact	B: $\beta = 3.66, t(16) = 2.60, SE = 1.41, p = .019$ B/I: $\beta = 1.82, t(205) = 2.19, SE = 0.83, p = .030, d = 0.31$ B/PI: $\beta = 2.63, t(16) = 1.84, SE = 1.43, p = .085, d = 0.92$	B: $\beta = 5.84, t(16) = 2.75, SE = 2.13, p = .014$ B/I: $\beta = 1.00, t(217) = 0.82, SE = 1.21, p = .411, d = 0.11$ B/PI: $\beta = 3.47, t(217) = 2.21, SE = 1.57, p = .028, d = 0.30$
Looking during unimanual toy manipulation	B: $\beta = 8.47, t(16) = 2.88, SE = 2.95, p = .011$ B/I: $\beta = 4.71, t(221) = 2.89, SE = 1.63, p = .004, d = 0.39$ B/PI: $\beta = 6.03, t(221) = 2.82, SE = 2.14, p = .005, d = 0.38$	B: $\beta = 3.10, t(16) = 1.82, SE = 1.71, p = .088$ B/I: $\beta = 2.72, t(217) = 1.88, SE = 1.45, p = .062, d = 0.26$ B/PI: $\beta = 5.74, t(217) = 3.05, SE = 1.88, p = .003, d = 0.41$
Looking during bimanual toy manipulation	B: $\beta = 0.49, t(16) = 1.42, SE = 0.35, p = .175$ B/I: $\beta = 0.31, t(221) = 0.88, SE = 0.35, p = .378, d = 0.12$ B/PI: $\beta = 0.12, t(221) = 0.27, SE = 0.45, p = .786, d = 0.04$	B: $\beta = 0.03, t(16) = 0.08, SE = 0.43, p = .937$ B/I: $\beta = 0.76, t(217) = 1.88, SE = 0.40, p = .061, d = 0.26$ B/PI: $\beta = 0.53, t(217) = 1.02, SE = 0.52, p = .311, d = 0.14$
Bouts of exploration (intensity)	B: $\beta = 23.56, t(16) = 6.86, SE = 3.43, p < .001$ B/I: $\beta = 2.79, t(205) = 1.62, SE = 1.73, p = .108, d = 0.23$ B/PI: $\beta = 8.07, t(16) = 2.70, SE = 2.99, p = .016, d = 1.35$	B: $\beta = 20.57, t(16) = 6.99, SE = 2.94, p < .001$ B/I: $\beta = 2.35, t(201) = 1.61, SE = 1.46, p = .110, d = 0.23$ B/PI: $\beta = 6.67, t(16) = 2.23, SE = 2.99, p = .041, d = 1.12$
Time performing single behaviors	B: $\beta = 33.77, t(16) = 10.76, SE = 3.14, p < .001$ B/I: $\beta = -6.88, t(16) = -2.42, SE = 2.84, p = .028, d = 1.21$ B/PI: $\beta = -12.56, t(205) = -4.26, SE = 2.95, p < .001, d = 0.60$	B: $\beta = 38.32, t(16) = 8.76, SE = 4.38, p < .001$ B/I: $\beta = -8.08, t(16) = -2.53, SE = 3.20, p = .022, d = 1.27$ B/PI: $\beta = -13.52, t(201) = -5.05, SE = 2.68, p < .001, d = 0.71$
Time performing combined behaviors	B: $\beta = 48.66, t(16) = 7.88, SE = 6.18, p < .001$ B/I: $\beta = 10.33, t(221) = 3.55, SE = 2.91, p < .001, d = 0.48$ B/PI: $\beta = 16.17, t(221) = 4.24, SE = 3.81, p < .001, d = 0.57$	B: $\beta = 45.51, t(16) = 7.34, SE = 6.20, p < .001$ B/I: $\beta = 12.33, t(217) = 4.41, SE = 2.80, p < .001, d = 0.60$ B/PI: $\beta = 22.36, t(217) = 6.15, SE = 3.64, p < .001, d = 0.83$
Variability of single behaviors	B: $\beta = 41.31, t(16) = 13.21, SE = 3.13, p < .001$ B/I: $\beta = 2.94, t(205) = 2.75, SE = 1.07, p = .006, d = 0.38$ B/PI: $\beta = 6.10, t(16) = 2.78, SE = 2.20, p = .013, d = 1.39$	B: $\beta = 35.47, t(16) = 14.83, SE = 2.39, p < .001$ B/I: $\beta = 4.10\ t(16) = 2.97, SE = 1.38, p = .009, d = 1.49$ B/PI: $\beta = 5.47, t(16) = 2.92, SE = 1.87, p = .010, d = 1.46$
Variability of combined behaviors	B: $\beta = 0.03, t(16) = 4.47, SE = 0.01, p < .001$ B/I: $\beta = 0.01, t(205) = 2.38, SE = 0.004, p = .018, d = 0.33$ B/PI: $\beta = 0.02, t(16) = 2.49, SE = 0.01, p = .024, d = 1.25$	B: $\beta = 0.02, t(16) = 4.47, SE = 0.004, p < .001$ B/I: $\beta = 0.01, t(201) = 2.92, SE = 0.002, p = .004, d = 0.41$ B/PI: $\beta = 0.01, t(16) = 2.57, SE = 0.004, p = .021, d = 1.29$
Either hand at the head level	B: $\beta = 0.24, t(16) = 2.23, SE = 0.11, p = .041$ B/I: $\beta = 0.16, t(205) = 2.25, SE = 0.07, p = .026, d = 0.31$ B/PI: $\beta = 0.43, t(16) = 1.08, SE = 0.40, p = .298, d = 0.54$	B: $\beta = 0.55, t(16) = 1.87, SE = 0.29, p = .081$ B/I: $\beta = -0.21, t(217) = -0.75, SE = 0.29, p = .457, d = 0.10$ B/PI: $\beta = 0.32, t(217) = 0.86, SE = 0.37, p = .389, d = 0.12$
Either hand at the chest level	B: $\beta = 15.97, t(16) = 3.96, SE = 4.04, p = .001$ B/I: $\beta = 1.62, t(221) = 0.78, SE = 2.09, p = .439, d = 0.10$ B/PI: $\beta = 5.06, t(221) = 1.85, SE = 2.73, p = .066, d = 0.25$	B: $\beta = 90.01, t(16) = 16.90, SE = 5.32, p < .001$ B/I: $\beta = 0.90, t(16) = 0.15, SE = 6.03, p = .883, d = 0.08$ B/PI: $\beta = -4.48, t(201) = -0.95, SE = 4.71, p = .343, d = 0.13$
Either hand at the hip level	B: $\beta = 97.14, t(205) = 74.95, SE = 1.30, p < .001$ B/I: $\beta = -1.77, t(16) = -0.77, SE = 2.31, p = .454, d = 0.39$ B/PI: $\beta = -5.61, t(16) = -1.76, SE = 3.19, p = .098, d = 0.88$	B: $\beta = 13.46, t(16) = 2.99, SE = 4.51, p = .009$ B/I: $\beta = 12.21, t(16) = 2.34, SE = 5.21, p = .032, d = 1.17$ B/PI: $\beta = 9.22, t(201) = 1.63, SE = 5.66, p = .105, d = 0.23$

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Arm flings to reach the toy	*B: β = 0.29, t(16) = 0.97, SE = 0.30, p = .345* *B/I: β = 0.16, t(221) = 1.04, SE = 0.16, p = .298, d = 0.14* *B/PI: β = 0.02, t(221) = 0.09, SE = 0.20, p = .930, d = 0.01*	*B: β = 0.02, t(16) = 0.31, SE = 0.07, p = .759* *B/I: β = 2.04, t(16) = 1.72, SE = 1.19, p = .105, d = 0.86* *B/PI: β = 1.76, t(201) = 1.35, SE = 1.31, p = .179, d = 0.19*
Trunk flings to reach the toy	*B: β = 1.06, t(16) = 2.14, SE = 0.50, p = .048* *B/I: β = -0.29, t(205) = -0.72, SE = 0.40, p = .471, d = 0.10* *B/PI: β = -0.64, t(16) = -1.00, SE = 0.64, p = .332, d = 0.50*	*B: β = 0.04, t(16) = 0.07, SE = 0.57, p = .943* *B/I: β = 0.75, t(217) = 1.37, SE = 0.55, p = .173, d = 0.19* *B/PI: β = -0.19, t(217) = -0.27, SE = 0.71, p = .789, d = 0.04*

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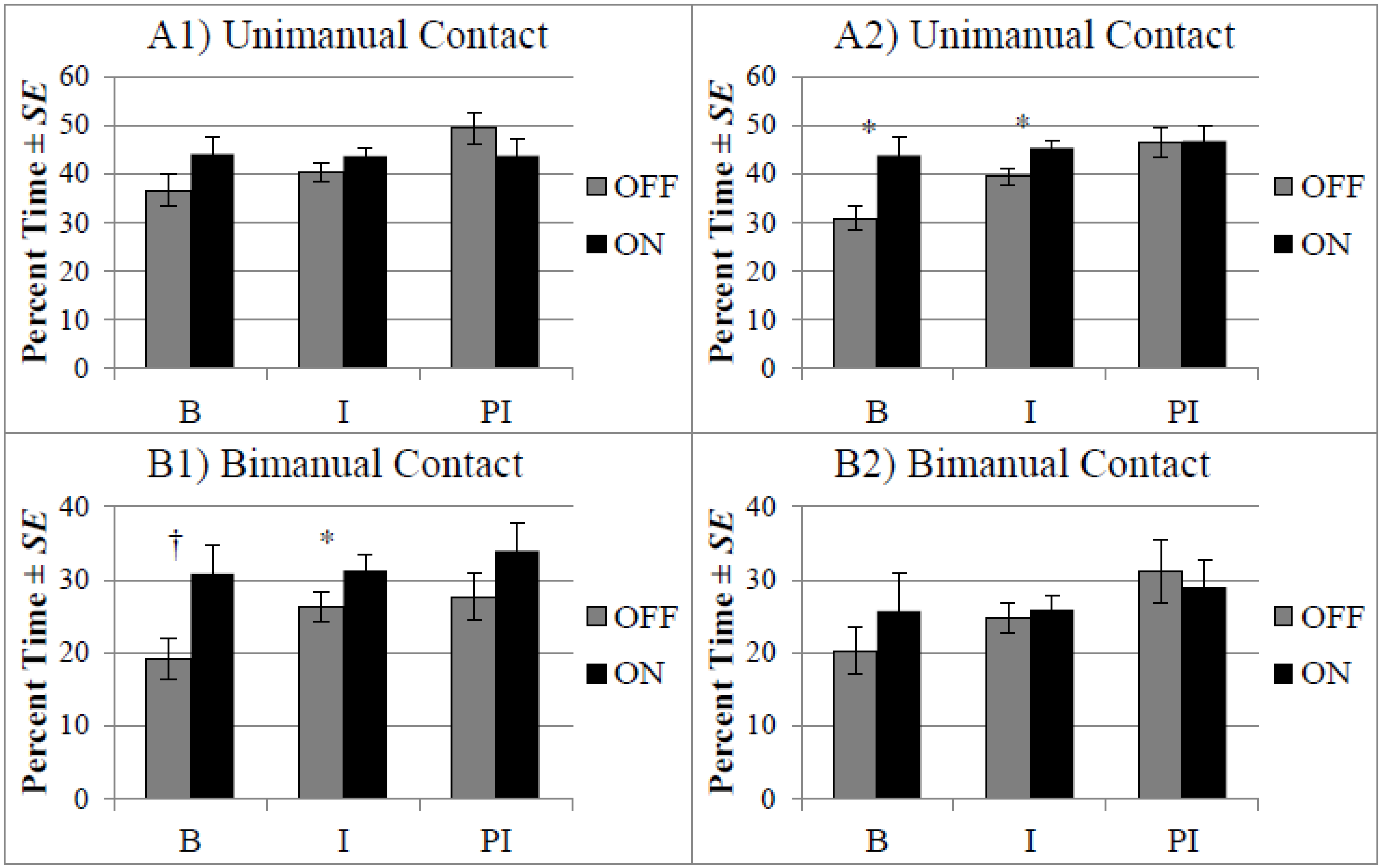
Figure S1. Summarized observed data for the outcome variables in the FLOOR (1) and SURFACE (2) assessments comparing children's performance during the Baseline, Intervention, and Post-Intervention Phases with the Playskin Lift™ exoskeletal garment donned (ON) or doffed (OFF); B = Baseline; I = Intervention; PI = Post-Intervention; * marks statistically significant effects ($p \leq .05$); † marks marginally significant effects ($p \leq .10$) of the Playskin within each phase.



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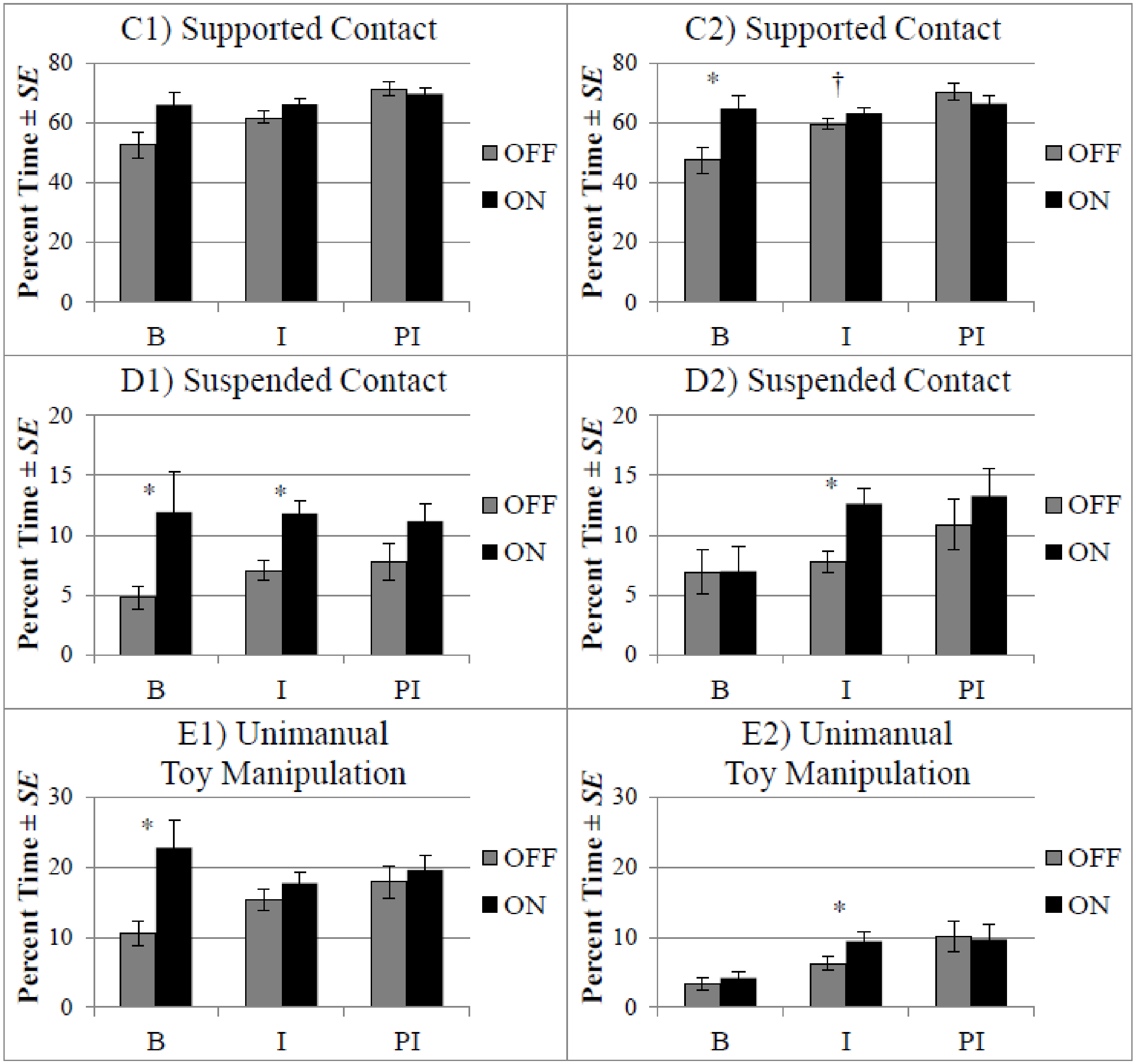

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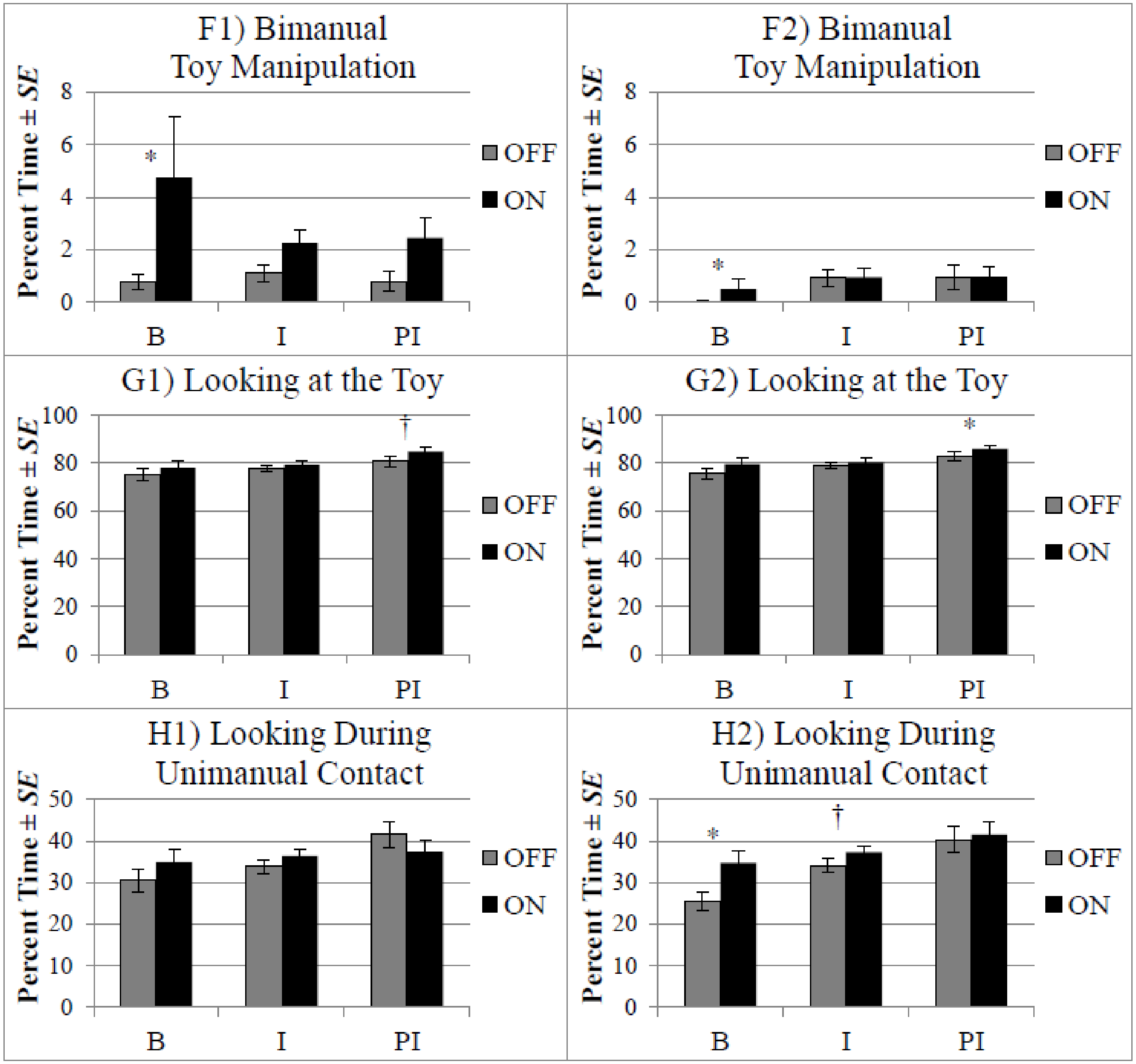

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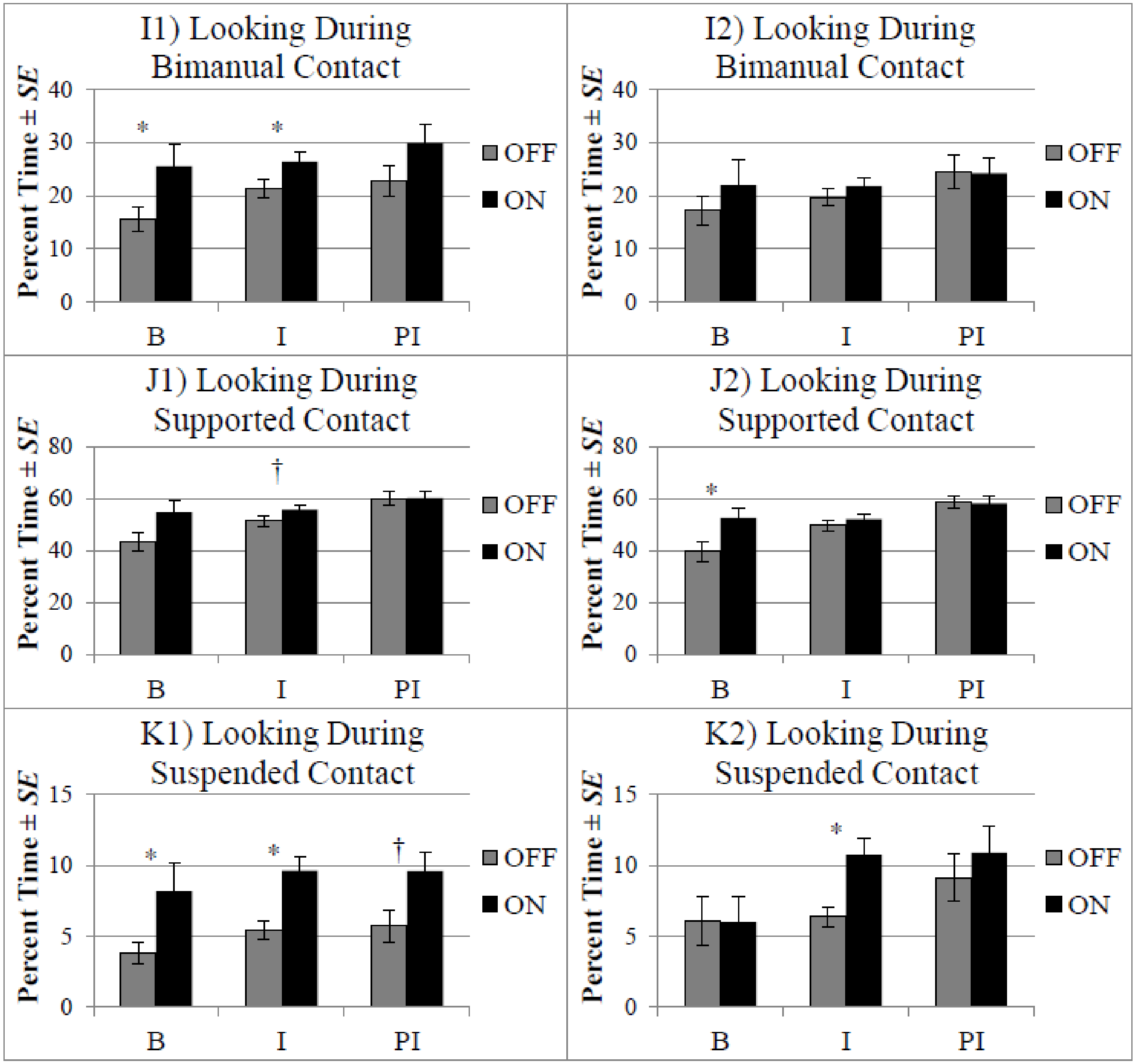

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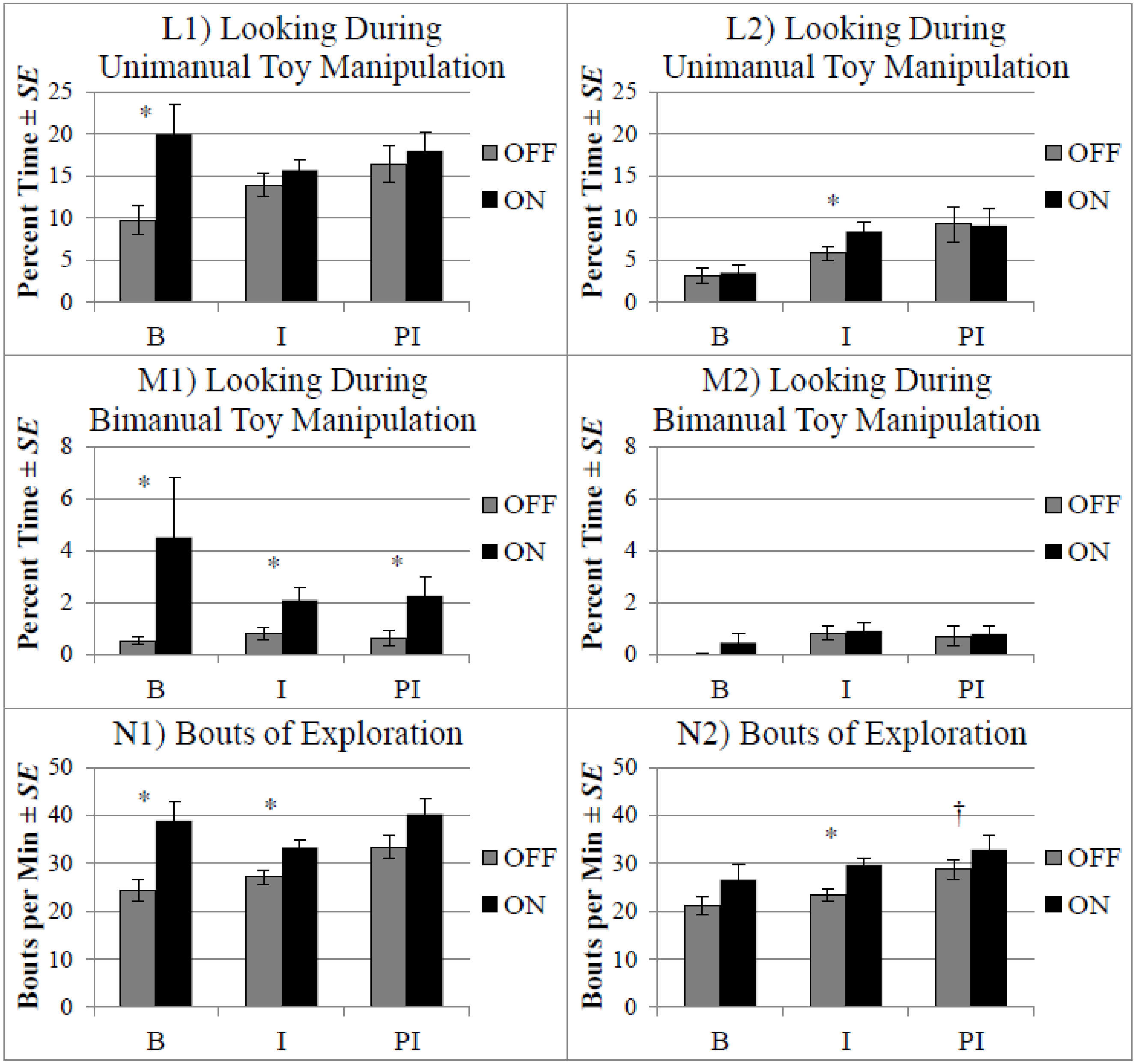

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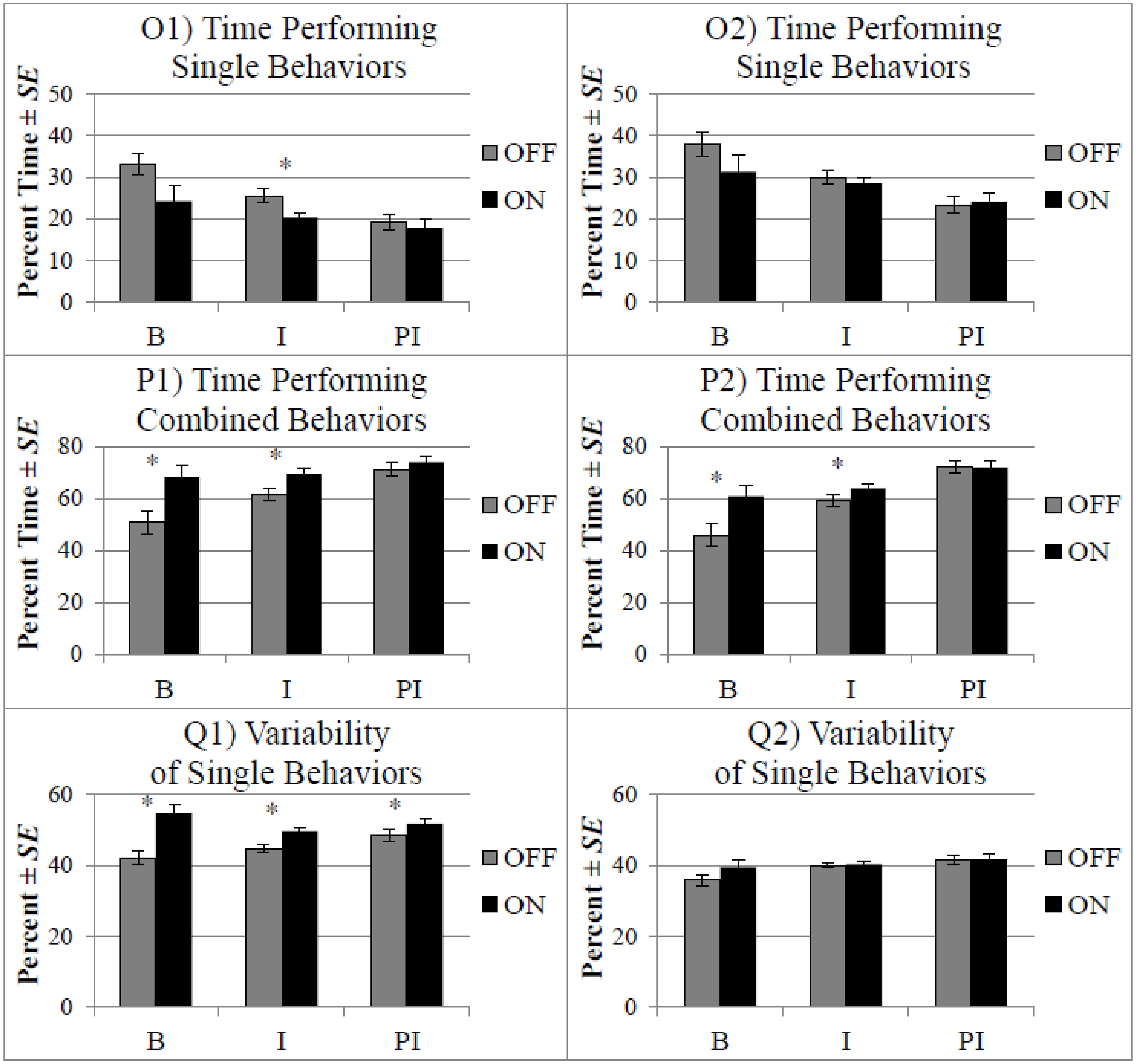

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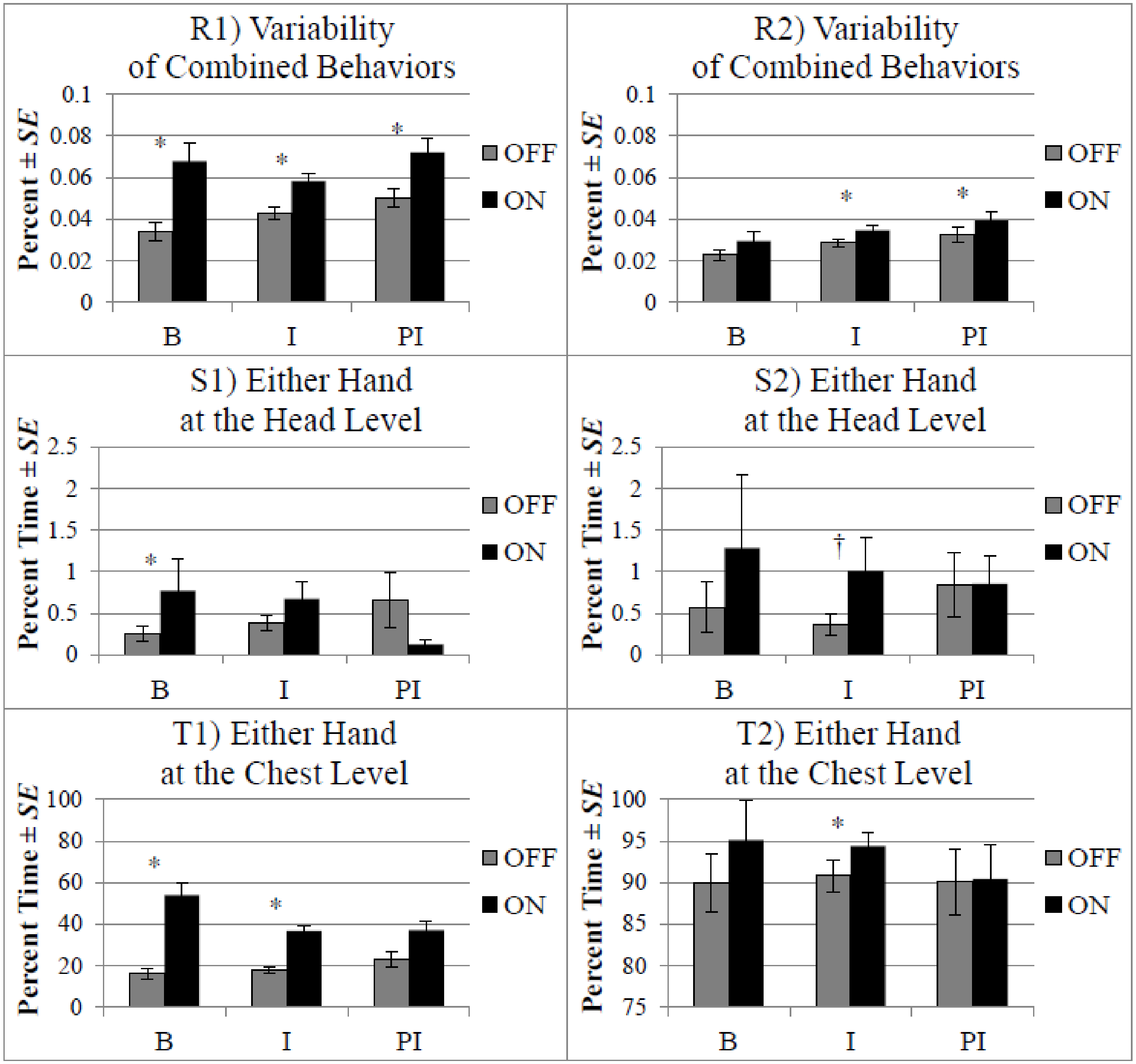

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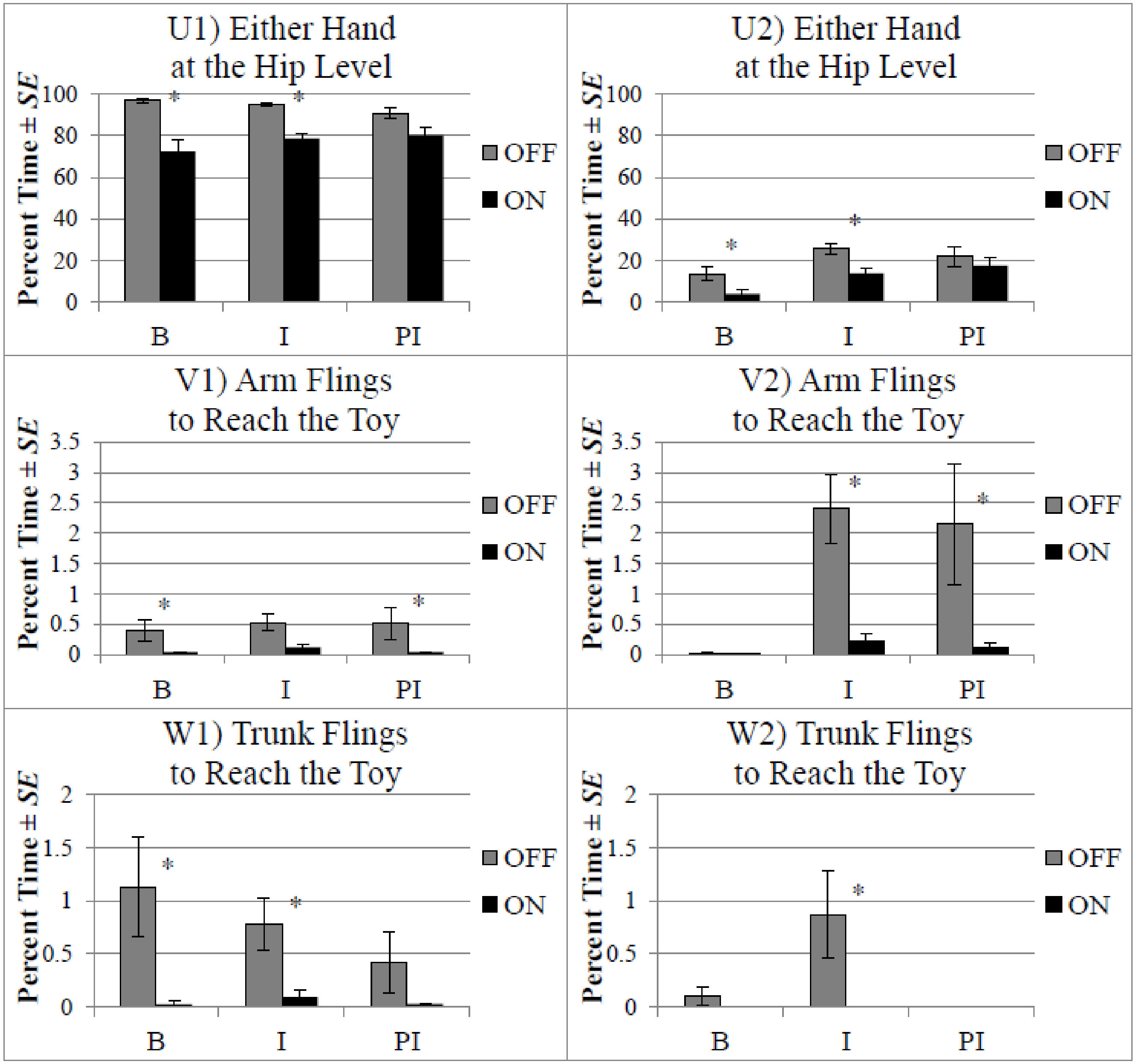

Intervention Instructions for Parents

Purpose of the Activities: The purpose of these activities is to help your child strengthen his/her arm muscles by using them in areas of space and in ways s/he has not done before.

Note: You can split the intervention activities if your child is tired or needs a break. Your child should be happy, playing, and having fun with these activities while learning to better move, gaining coordination, and increasing muscle strength.

Directions:

1) Try to perform these activities every day knowing that there will be occasions when you will miss a day or two.
2) Your child should be in a comfortable seated position, such as sitting on the floor.
3) Your child should be wearing the Playskin garment.
4) **Place one set of inserts into vinyl tunnels under the garment's sleeves.**
    a. Play with your child and set up toys for him/her that will challenge and encourage arm movement above the supported arm height and all the way down through floor level. This could involve placing toys on elevated surfaces or stools, using bucket-like toys that allow for putting things in and taking things out, using stacking toys, or handing your child toys at different areas of the play space (high, low, left, and right). Focus on helping your child to explore moving to the left, right, middle, up, and down. This will help teach him/her how to move in these areas.
    b. Perform this play for about 20 minutes each day when your child is in a happy and alert mood.
5) **Repeat #4 using the other pair of inserts**; perform this play for about 20 minutes each day. Thus, the total playtime with both pairs of inserts should be about 40 minutes per day.
6) **If you find that one set of inserts works best, you may use just that set for 40 min per day.**
7) **Record in your daily log:**
    a. The total time your child wore the garment with inserts while performing the intervention activities that day. The goal for the intervention time each day is about 40 minutes.
    b. The total time your child wore the garment with inserts that day (intervention time plus any extra time). For example, total time wearing the garment on a particular day may be 2 hours, while time performing intervention activities may be 40 minutes. If you miss a day, simply note that it was worn for 0 minutes.