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Hand-Use Preferences for Reaching and Object Exploration in Children with Impaired Upper Extremity Functioning: The Role of Environmental Affordances

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Abstract: Infants and young children with weakened or impaired upper extremity functioning often develop a strong hand-use "preference" for reaching and object manipulation. While "preferring" their stronger hand, they often partially or completely ignore their "non-preferred" hand. Such manual lateralization might impede complex object exploration, which would negatively affect children's cognitive development. The question is whether environmental affordances would significantly affect children's manifested hand-use "preferences" by promoting the use of the "non-preferred" hand. The current sample included 17 children (5 males; 13.9 ± 8.7 months at baseline) with arthrogryposis multiplex congenita (arthrogryposis). The reaching and object exploration of the children were evaluated longitudinally across a 6-month period with and without the Playskin Lift^{TM} exoskeletal garment (Playskin). Results showed that the use of the Playskin increased both unimanual and bimanual object contact. Also, when anti-gravity support was provided to the arms by the Playskin, children significantly increased the use of their non-preferred hand, which correlated with improved quality of object play—more bimanual object interaction and greater intensity, variability, and complexity of exploration. These findings suggest that hand-use "preference" in children with arthrogryposis is quite malleable during early development. It is likely that children with impaired upper extremity functioning do not "prefer" to use a particular hand but, rather, cannot afford using both hands due to their limited muscular or manual abilities. Importantly, environmental affordances (i.e., anti-gravity support for the arms) might significantly affect the early development of manual lateralization, with potential implications for children's quality of object exploration and future cognitive development.

Keywords: reaching; object exploration; hand-use preference; arthrogryposis multiplex congenita; Playskin Lift^{TM} exoskeletal garment; children

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1. Introduction

Hand-use preference, often referred to as handedness, is usually defined as a consistent favoring of one hand over the other while performing everyday tasks. For humans, there is a remarkable asymmetry in the distribution of hand preferences, with about 10% of the population showing a left-hand preference, e.g., [1,2]. Hand preference (or manual lateralization) is a manifestation of the hemispheric lateralization in manual control, with the control of precise movements in the hand and fingers deriving from neural activity in the contralateral hemisphere [3–6]. Hemispheric lateralization increases the efficiency of information processing through parallel processing, redundancy reduction, and interhemispheric conflict prevention [7–9]. If hand preference is a marker of hemispheric lateralization, a stronger hand-use preference should result in better developmental outcomes [10]. Indeed, previous research found that early development of distinct and consistent hand preferences (irrespective of their direction—right or left) might stimulate children's object management (i.e., object storage [11]), object construction (i.e., block stacking onset and skill level [12]), tool-use [13], language skills [14–17], and cognition [18,19].

However, previous research found no difference in role-differentiated bimanual manipulation between 9–14-month-old children with vs. without a distinct and stable hand preference [20]. Instead, researchers suggested that *coupling of the hands in bimanual reaching* facilitates role-differentiated bimanual manipulation of objects [21]. Thus, it is likely that the relation between the strength of hand preference and developmental outcomes has an inverted U shape: while a lack of manual lateralization might not support optimal developmental outcomes in object exploration, language, and cognition, very strong manual lateralization that eliminates spontaneous bimanual reaching might also negatively affect global development. The question is how to promote a healthy level of manual lateralization, especially in children with motor impairments.

1.1. Typical Development of Hand-Use Preferences

Although some researchers suggested that hand-use preferences are orchestrated by hypothetical genetic predispositions [3], others provided explicit examples of how biological and environmental factors might affect the development of hemispheric specialization in general and hand preference in specific [22]. The *modified progressive lateralization theory* acknowledges the existence of early structural and functional asymmetries but also suggests cascading development of those asymmetries throughout the lifespan, with early asymmetries feeding into asymmetries manifested later in more complex skills and tasks [22–24].

Development of hemispheric specialization for manual control might begin before the conception of an organism: zygotic asymmetries, coupled with asymmetries of the intrauterine environment, produce early signs of hemispheric lateralization [25]. Asymmetries of the fetal position in utero influence the neonate's supine head orientation preference [26–30]. The latter, in turn, cascades into lateralized asymmetries in hand/arm activation, as well as differences in visual, tactile, and proprioceptive feedback that the infant receives from hand/arm movements [31]. Such sensorimotor asymmetries facilitate the formation of the "action systems" that underlie the lateralized use of the hands [23,31]. As a result, the head orientation preferences displayed by neonates influence their development of hand-use preferences for reaching [28,31]. Next, manual lateralization for reaching concatenates into hand preferences for more sophisticated skills, such as unimanual manipulation of objects, role-differentiated bimanual manipulation, object construction, and tool use [13,24,32–35].

1.2. Development of Hand-Use Preferences in Children with Motor Delays or Disabilities

Children born preterm may deviate from the typical developmental patterns of manual asymmetries. Preterm birth is often associated with brain injuries (e.g., periventricular leukomalacia) that may create atypical asymmetries in the structure and function of the cerebral hemispheres, as well as deficits in interhemispheric connectivity [36–44]. Atypical brain asymmetries may interfere with the optimal development of posture and movement control, spontaneous movements, and visuomanual coordination, thus undermining reaching and object interaction in children born preterm [45–49]. Consequently, infants born preterm might show diminished bimanual engagement with objects, as well as significantly lower variability and complexity of their object exploration behavior [50–53].

Prenatal or perinatal brain injuries are also the leading cause of cerebral palsy (CP)—an umbrella term covering permanent, non-progressive neurological disorders of posture and movement control that negatively affect children's motor function [54–59]. Similarly, early stroke may damage different brain regions and result in impaired motor function [60,61]. The predominant type of CP is unilateral (or hemiplegic) CP, affecting one side of the body (contralateral to the locus of the brain insult) and diminishing the child's ability for tasks that require coordinated use of both hands [62]. Children with hemiplegic CP tend to "disregard" the affected limb and avoid using it in daily activities. The resulting lack of motor practice weakens the neuromotor pathways, diminishes muscle strength, and reduces the likelihood of the child to spontaneously engage the affected hand in motor tasks that could provide "practice" and improve motor control and function [63,64]. As a result, the tendency to rely only on one hand for everyday activities not only impedes children's bimanual coordination and complex object exploration but also negatively affects their self-care abilities, independence, and quality of life [62,63,65–67].

While most typically developing children slowly develop a distinct hand-use preference by the age of 3–7 years [68], children with motor delays or impairments might exhibit a more pronounced hand preference early on [69,70]. There are a few reasons for a strong "hand preference" in children with motor impairments. First, manual asymmetry may be the reflection of cerebral asymmetry formed as a result of an early brain injury [3,4,6,71]. Second, in search of the most efficient and effective ways to interact with their environment, children with motor impairments may reinforce the use of the less-affected hand for everyday activities simply because it yields better results; subsequent "disregard" of the more affected hand and continuous use of the less affected hand further reinforce the displayed manual lateralization [63,64,72]. In this case, does the displayed manual lateralization in children with movement impairments represent children's true hand "*preference*" or, rather, the result of neurological and physical *constraints* that limit the engagement of both hands in everyday activities?

Children born preterm and those diagnosed with CP also exhibit higher rates of left-handedness or no distinct hand preference; whereas left-handedness in typical populations across different cultures is about 10% [1,2,73], up to 50% of children with preterm birth, birth asphyxia, or brain insults leading to CP may manifest left-hand preference at ages 2–15 years, e.g., [69,70,74,75]. These disproportionately high rates of "pathological left-handedness" [69,74] can be attributed to manual asymmetries developing in the aftermath of structural and functional hemispheric reorganizations due to early brain insults. Since there is an equal (50/50%) probability of a brain insult occurring in either hemisphere, it is not surprising that the probability of left-handedness associated with the damage to the right hemisphere may reach 50%.

Although a considerable body of research focused on hand-use patterns in children born preterm or with CP, other populations of children with motor impairments received much less attention. For example, previous research did not explore in detail hand use in children with arthrogryposis multiplex congenita (arthrogryposis). Arthrogryposis is a non-progressive, congenital neuromuscular disorder characterized by significant muscle weakness, joint contractures, and impaired movement in the upper and/or lower extremities [76–78]. Children with arthrogryposis often experience considerable difficulties with anti-gravity arm movement, which negatively affects their reaching abilities and object exploration, especially the manipulation of objects that requires simultaneous engagement of both hands. For example, previous research showed a lack of unassisted bimanual object contact in an 8–13-month-old child with arthrogryposis [79]. Similarly, while unassisted *unimanual* object contact and manipulation were performed for 36.52% and 9.72% of the assessment time, respectively, *bimanual* contact and manipulation were manifested only for 18.05% and 0.76% of the assessment time, respectively, in 6–35-month-old children with arthrogryposis [80]. Note that there is a lack of previous research analyzing unilateral hand use in children with arthrogryposis from the perspective of manual lateralization. Working with children having arthrogryposis, we noticed that they tended to develop very early and strong hand preferences. However, in contrast to children with CP, manual lateralization of children with arthrogryposis is not due to any brain insults but, rather, stems from muscle weakness and joint contractures. Formal research on hand-use preferences of children with arthrogryposis is needed to better understand how to promote optimal manual lateralization in this population.

1.3. Environmental Affordances Might Affect Children's Hand Use

Previous research showed that experimental manipulation of environmental affordances can significantly affect not only the frequency and quality of hand use but also hand preferences in children with motor impairments [81–85]. Environmental affordances can be manipulated in the form of subtraction or addition. Examples of the *subtraction* in environmental affordances would be forced-use therapy (FUT [86,87]), constraint-induced movement therapy (CIMT [63,88–90]), or interventions using a novel PlaySkin Duo$^{\text{TM}}$ (Move 2 Learn Innovation Lab, Department of Physical Therapy, University of Delaware, Newark, DE, USA) soft exoskeletal garment (PlaySkin Duo [10]). In FUT and CIMT therapies, the child's better functioning hand is casted, thus significantly preventing its use, especially for activities requiring fine-motor movements. As a result, the child is forced to use the more affected and previously "non-preferred" (often neglected) hand for everyday activities. The PlaySkin Duo functions in a way similar to FUT and CIMT, as it restricts the movement of the child's less affected hand/arm by connecting it to the garment's torso with an elastic band. This makes it challenging for the child to move the less affected arm, thus stimulating the use of the "non-preferred" hand.

Examples of *addition* in environmental affordances would be bimanual training (BIM [91,92]), hand–arm bimanual intensive therapy (HABIT [82,93]), and interventions using "sticky mittens" [94], a Velcro band [95], or anti-gravity support for the arms with the Playskin Lift$^{\text{TM}}$ soft exoskeletal garment (Playskin [80]). Both BIM and HABIT therapies explicitly reinforce the use of the more affected hand through repeated prompts from a physical therapist for the child to use that hand. "Sticky mittens" allow the child an experience of easy "grasping" of an object with the more affected hand, even when its fine-motor abilities would not allow a grasp. Such scaffolded grasps may facilitate the child's motivation to use the more affected hand [94,96]. The Playskin provides anti-gravity assistance via springy, mechanical inserts within a garment to assist in raising children's arms to the desired level of shoulder flexion, thus increasing the workspace where children can reach for and interact with toys [97].

Previous research showed significant improvements in hand functioning as a result of the aforementioned therapies for children with CP. For example, CIMT produced significant improvements in spontaneous use of the more affected hand, with gains in both frequency and quality of the movements sustained for up to 6 months after the conclusion of the therapy in 7–96-month-old children with congenital hemiplegia [81,83,84,98]. Similarly, HABIT significantly improved the use of the affected hand and bimanual hand use in 3.5–15.5-year-old children with hemiplegic CP [82]. Despite significantly advancing children's unimanual activity, both FUT and CIMT seem to be less effective in training bimanual coordination than BIM or HABIT in 2–15.5-year-old children [82,86,92]. Intervention with the Playskin also showed significant improvements in both unimanual and bimanual functioning in 6–35-month-old children with arthrogryposis [80,97]. However, previous research on the effects of aforementioned interventions on hand use in children with CP or arthrogryposis mostly focused on functional gains in manual activity rather than manual lateralization.

1.4. Current Study

The goal of the current study was to test the effect of environmental affordances on manifested hand-use preference during early development in children with motor impairments. We hypothesized that the Playskin Lift$^{\text{TM}}$ exoskeletal garment (Playskin), providing anti-gravity assistance to children's arms, would improve children's ability to reach for and explore objects, making it easier for children to use both the preferred and the non-preferred hand, which might lead to significant changes in their demonstrated hand-use preference. The following *hypotheses* were tested in children with arthrogryposis having muscular weakness or motor impairments: (***H1***) the Playskin would improve reaching and object exploration; (***H2***) the Playskin would increase the use of the non-preferred hand, thus reducing the strength of children's demonstrated hand-use preference; and (***H3***) demonstrated hand-use preference would be significantly associated with the quality of object exploration.

2. Methods

2.1. Participants

An a priori power analysis was performed in GLIMMPSE software, which is appropriate for longitudinal designs (http://glimmpse.samplesizeshop.org/, accessed on 27 November 2023). The Hotelling Lawley Trace statistical test suggested a sample size of 16 (two-tailed, $\alpha = 0.05$, $power \geq 0.80$).

The current study was based on a sample of 17 children with arthrogryposis (5 males; age at the baseline 13.9 ± 8.7 months, with the range of 5.8–35.0 months). The sample consisted of 82.4% Caucasian, 11.7% African American, and 5.9% Asian participants, and represented a wide range of household incomes—11.8% with $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.

Participants were recruited in the study through personal referrals and social media. Local participants ($n = 6$) were tested in person, whereas distant families ($n = 11$) followed standardized written instructions to reproduce the appropriate testing setup and videotape all the assessments. The following study eligibility criteria were applied for children: (1) passive shoulder flexion greater than 100 degrees; and (2) inability to independently lift the arms to 90° of shoulder flexion. An exclusion criterion was the lack of independent head control. All enrolled children had adequate head control; twelve children could sit independently, and five needed assistance while sitting. In this longitudinal study, only 5% of the data were missing ($M = 1.82$, $SD = 1.76$); all data were missing at random. The study was conducted with oversight from the Institutional Review Board at the University of Delaware, which approved the study protocol on 20 August 2015 (356189). Parents of participating children gave their informed consent for the inclusion of their children in the study. Upon completion of the study, participants received monetary compensation ($50).

2.2. Materials

The current study implemented an exoskeletal garment, the Playskin Lift$^{\text{TM}}$ (see Figure 1A), that provides anti-gravity assistance for children's arms [99]. The Playskin uses springy inserts made of bundled steel wires placed into vinyl tunnels under the sleeves of a soft garment to provide anti-gravity support and assist in raising children's arms through 90° of shoulder flexion.

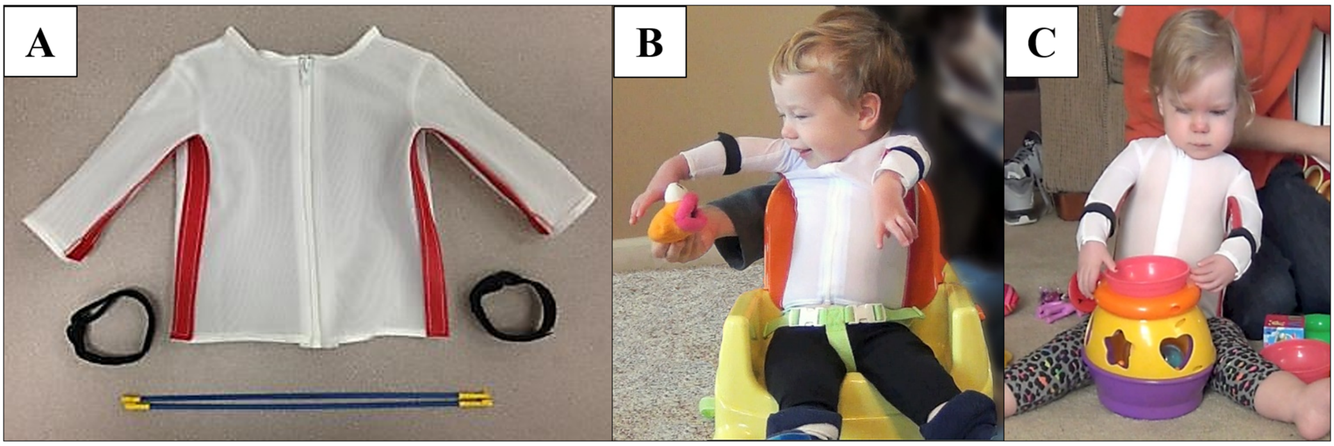

Figure 1. The Playskin Lift$^{\text{TM}}$ exoskeletal garment with vinyl tunnels under the sleeves for placement of springy inserts and arm straps (at the bottom) to maintain inserts directly under the arms for optimal anti-gravity support (**A**); a child wearing the Playskin exoskeleton during the reaching assessment (**B**); a child wearing the Playskin exoskeleton during the object exploration assessment (**C**).

2.3. Procedures

All participants were tested in their home environment biweekly throughout a 6-month period. During each testing session, children participated in a standardized reaching assessment and an object exploration assessment. Both assessments were conducted without and with the Playskin (OFF and ON experimental conditions, respectively). The order of the conditions was alternated at each visit to control for possible effects of task familiarity or fatigue. In the ON condition, we used springy inserts that supported children's arms throughout about 70° of shoulder flexion.

During the *reaching assessment* (Figure 1B), children were presented with an object (2 × 4-inch colorful, noise-making toy) within reach at the hip, chest, and eye levels. The object was presented for 60 s at each level, with a total of 180 s across the three levels [100]. For the purpose of this study, data were averaged across the three object presentation levels. Raw data associated with each level are illustrated in the Supplementary Materials (Figure S1). Depending on their sitting ability, children were sitting in a high chair or booster seat.

During the *object exploration assessment* (Figure 1C), children participated in semi-structured free play with a standard set of age-appropriate toys for five minutes while sitting on the floor. Depending on their sitting ability, children were supported or not supported at the trunk by their caregivers or pillows. Children were free to play with any of the presented toys; neither a caregiver nor researcher interfered with the children's play.

The study setup was consistent across all participants and testing sessions. All assessments were performed while children were in a positive or neutral mood. If a child displayed a negative mood, the testing was paused for a rest break or was rescheduled. The assessments were videotaped with frontal- and side-view cameras for behavioral coding of synchronized videos using OpenSHAPA software (https://github.com/OpenSHAPA accessed on 27 November, 2023, GitHub, San Francisco, CA, USA).

2.4. Outcome Measures

For both assessments, trained research assistants recorded the duration of the following behaviors: (1) *Right-Handed Contact*—when the child's right hand contacted an object; (2) *Left-Handed Contact*—when the child's left hand contacted an object; and (3) *Visual Attention*—when the child's eyes were directed toward an object. In addition, for the object exploration assessment, we recorded the duration of object manipulation—instances when both hands were engaged in object interaction, with one hand playing a passive, supporting role and the other being actively engaged in manipulating a movable part of an object (e.g., pushing a button, rotating a spinner) or two objects (e.g., stacking, inserting, taking out). Thus, we coded the duration of: (1) *Right-Handed Object Manipulation*—when the child used the right hand for active object manipulation; and (2) *Left-Handed Object Manipulation*—when the child used the left hand for active object manipulation.

Next, Filemaker software (version 16, Santa Clara, CA, USA) was used to determine instances of co-occurring behaviors (e.g., contacting an object simultaneously with the right and left hands; contacting an object while looking at it), resulting in the following additional measures: (1) *Bimanual Contact*—when both hands contacted an object; (2) *Bouts of Behavior*—the number of transitions from one behavior to another normalized per minute (measure of behavioral intensity); (3) *Variability of Behaviors*—percent of the total possible individual behaviors actually performed by the child (a measure of behavioral variability); and (4) *Combined Behaviors*—when the child used more than one behavior simultaneously to interact with an object (measure of behavioral complexity).

The following variables were also calculated: (1) *Unimanual Contact*—the sum of contacts with only the right- or left-hand; (2) *Hand Preference Index* (HPI)—calculated per each visit, each participant, for both object contact and manipulation using the formula [$HI = (R - L)/(R + L)^{1/2}$], where R and L represented the percent time for right- and left-handed contact/manipulation, respectively [HPI is basically a z-score used to estimate the relative probability of a child's hand-use preference at a certain time point and mark both the magnitude and direction of the hand preference [101]. HPI = 0 means equal involvement of the two hands in a specific motor activity; positive HPI signifies greater use of the right hand, whereas negative HPI points to higher involvement of the left hand. Since, in this study, we were interested in the magnitude, or strength, of hand-use preference rather than its direction, HPI per se was not used in any statistical analyses. Instead, we used the absolute value of the HPI, marking the magnitude/strength of children's hand preference.]; (3) *Strength of Hand Preference*—calculated for both object contact and manipulation as an absolute value of the corresponding HPI; (4) *Contact with the Non-Preferred Hand*—if the HPI for object contact was negative, then the Right-Handed Contact score was used; if the HPI was positive, then the Left-Handed Contact score was used; and (5) *Manipulation with the Non-Preferred Hand*—if the HPI for object manipulations was negative, then the Right-Handed Object Manipulation score was used; if the HPI was positive, then the Left-Handed Object Manipulation score was used. All the aforementioned measures, with the exception of *Bouts of Behavior*, were calculated as a percentage of the assessment time by dividing each behavior's cumulative duration by the total assessment time.

Coding reliability was established for 20% of the data (randomly selected videos for re-coding) as a proportion of codes that "agreed" across two coding rounds within the same coder (intra-rater agreement) or between two coders (inter-rater agreement). Using the formula [Agreed/(Agreed + Disagreed)] $*$ 100, intra- and inter-rater agreement was $\geq$85% for both the reaching and object exploration assessments.

2.5. Statistical Analyses

For the purpose of this study, the data were averaged across all visits per condition and participant. Results were considered statistically significant at $\alpha \leq 0.05$. In addition, Cohen's d effect size was reported for all t-tests to mark the magnitude and meaningfulness of each effect: $d = 0.2$ small, $d = 0.5$ medium, $d = 0.8$ large, and $d = 1.2$ very large effects [102,103].

2.5.1. The Effect of the Playskin on Children's Reaching and Object Exploration Ability (H1)

Paired-samples t-tests (two-tailed) were performed in IBM SPSS statistics software (version 29; IBM Corp., Armonk, NY, USA) to compare scores between the experimental conditions (using a dummy-coded *Condition* variable: 0 = OFF; 1 = ON) for the following outcomes: right-handed contact, left-handed contact, unimanual contact, and bimanual contact. To evaluate the magnitude of observed changes in the raw outcome scores between the OFF and ON conditions, we calculated an *absolute change* (Absolute Change = ON − OFF) and a *relative change* (Relative Change = (ON − OFF)/OFF $*$ 100%), with ON being a score for a specific outcome observed in the ON condition, and OFF signifying a score associated with the OFF condition.

The aim of these analyses was to test the hypothesis that using the Playskin significantly improves children's ability to engage with objects both unimanually and bimanually. Although these analyses did not directly address the effect of external support (environmental affordances) on children's hand-use preferences, they provided important information about whether the provision of external support altered children's interaction with objects.

2.5.2. The Effect of the Playskin on Children's Hand-Use Preferences (H2)

Paired-samples t-tests (two-tailed) were performed in SPSS to compare scores between the OFF and ON conditions for the following variables: object contact with the non-preferred hand, object manipulation with the non-preferred hand, and the strength of hand preference for both object contact and manipulation. Also, absolute and relative changes in scores between the OFF and ON conditions were calculated (see above). The goal of these analyses was to directly test whether the use of anti-gravity support for the arms of children with muscle weakness and impaired motor functioning would promote the use of the "non-preferred" hand and reduce the strength of the apparent hand-use "preference".

2.5.3. Relation between Hand-Use Preferences and Quality of Object Exploration (H3)

Pearson correlations (two-tailed) in SPSS were performed to relate object contact with the non-preferred hand and the strength of hand preference for object contact to bimanual contact, visual attention, combined behavior, bouts of behavior, and variability of behavior. The objective of these analyses was to determine whether the observed use of the non-preferred hand and the strength of hand preference (due to Playskin use) significantly correlated with the enhanced play quality, defined here as increased bimanual object interaction and visual attention to objects, as well as improved intensity, variability, and complexity of exploration.

3. Results

3.1. The Effect of the Playskin on Children's Reaching and Object Exploration Ability (H1)

Reaching Assessment. The use of the Playskin resulted in a significant increase in right-handed (absolute change 5.35, relative change 31.23%, $p = 0.001$), unimanual (absolute change 7.84, relative change 24.67%, $p = 0.005$), and bimanual (absolute change 2.59, relative change 32.33%, $p = 0.035$) contact, whereas no difference between the OFF and ON conditions was observed for left-handed contact ($p = 0.157$, see Figure 2). Statistical parameters for these analyses are presented in Table 1.

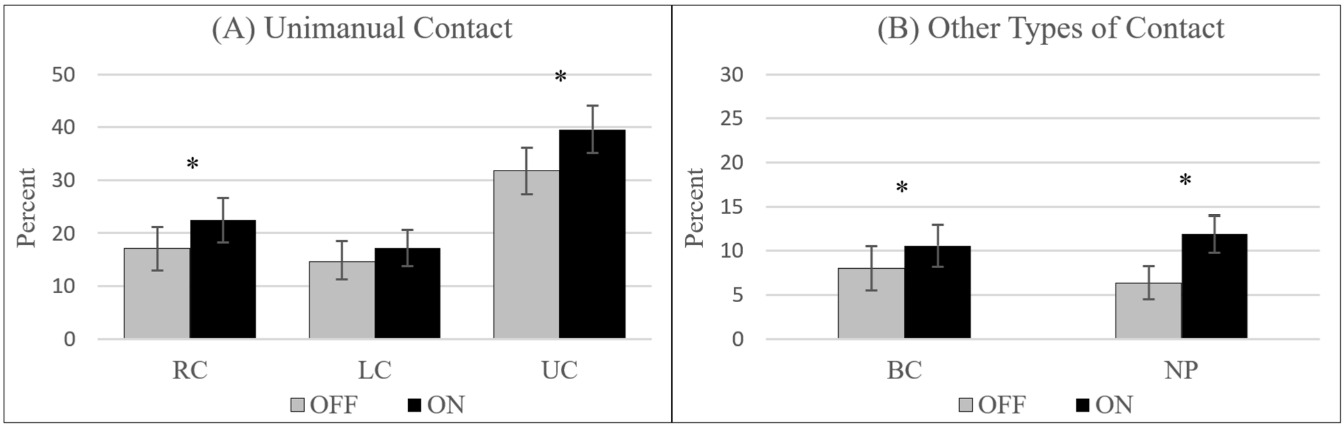

Figure 2. Average (*Mean* ± *SE*) percent time children contacted objects during the ***reaching assessment*** in the OFF and ON experimental conditions; RC = right-handed contact; LC = left-handed contact; UC = unimanual contact; BC = bimanual contact; NP = contact with the non-preferred hand; significant differences ($alpha \leq 0.05$) are marked with an asterisk.

Table 1. Raw data (*Mean* ± *SD*) and statistical parameters (with Cohen's *d* effect sizes) for paired-samples *t*-tests (two-tailed) evaluating differences in children's manual ability and hand-use preferences between the OFF (without the Playskin) and ON (with the Playskin) conditions during the ***reaching assessment***.

Variables	OFF Condition	ON Condition	Statistical Parameters
Right-Handed Contact	17.13 ± 16.83	22.48 ± 17.31	$t(16) = -3.85$, $\mathbf{p = 0.001}$, $d = 1.92$
Left-Handed Contact	14.65 ± 16.24	17.15 ± 14.12	$t(16) = -1.48$, $p = 0.157$, $d = 0.74$
Unimanual Contact	31.78 ± 18.11	39.62 ± 18.37	$t(16) = -3.24$, $\mathbf{p = 0.005}$, $d = 1.62$
Bimanual Contact	8.01 ± 10.47	10.60 ± 9.88	$t(16) = -2.30$, $\mathbf{p = 0.035}$, $d = 1.15$
Contact with the Non-Preferred Hand	6.37 ± 7.84	11.89 ± 8.56	$t(16) = -3.88$, $\mathbf{p = 0.001}$, $d = 1.94$
Strength of Hand Preference for Object Contact	3.67 ± 2.05	3.75 ± 1.87	$t(16) = -0.60$, $p = 0.558$, $d = 0.30$

Note. Statistically significant ($p \leq 0.05$) results are marked in bold.

Object Exploration Assessment. There was no difference between the two experimental conditions (OFF vs. ON) in right-handed contact ($p = 0.121$), left-handed contact ($p = 0.972$), unimanual contact ($p = 0.208$), or bimanual contact ($p = 0.097$, see Figure 3). Corresponding statistical parameters are presented in Table 2.

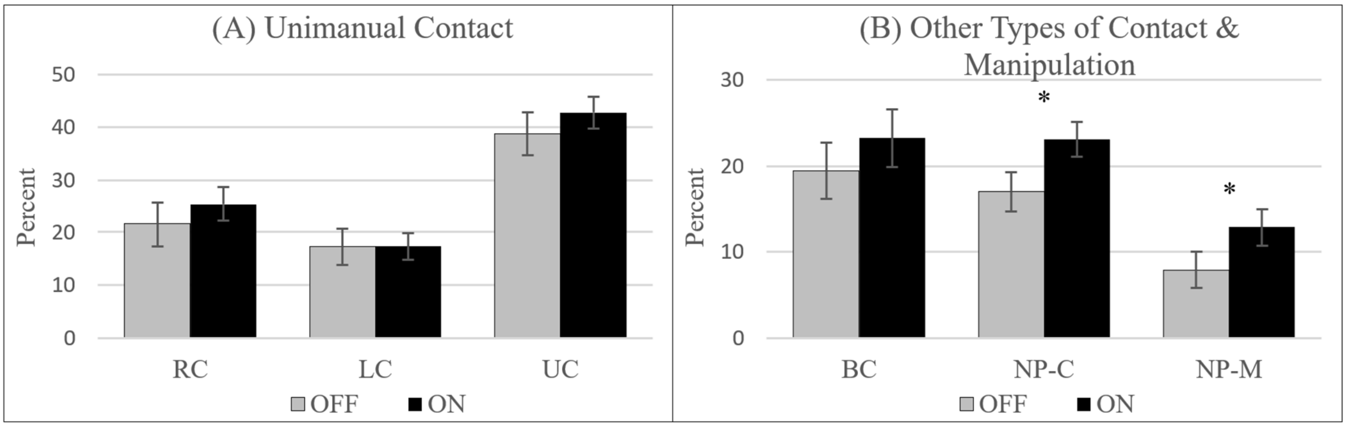

Figure 3. Average (*Mean* ± *SE*) percent time children contacted and manipulated objects during the ***object exploration assessment*** in the OFF and ON experimental conditions; RC = right-handed contact; LC = left-handed contact; UC = unimanual contact; BC = bimanual contact; NP-C = contact with the non-preferred hand; NP-M = manipulation with the non-preferred hand; significant differences (*alpha* $\leq$ 0.05) are marked with an asterisk.

Table 2. Raw data (*Mean* ± *SD*) and statistical parameters (with Cohen's *d* effect sizes) for paired-samples *t*-tests (two-tailed) evaluating differences in children's manual ability and hand-use preferences between the OFF (without the Playskin) and ON (with the Playskin) conditions during the ***object exploration assessment***.

Variables	OFF Condition	ON Condition	Statistical Parameters
Right-Handed Contact	21.57 ± 17.72	25.49 ± 13.51	$t(16) = -1.64$, $p = 0.121$, $d = 0.82$
Left-Handed Contact	17.24 ± 14.08	17.30 ± 10.38	$t(16) = -0.04$, $p = 0.972$, $d = 0.02$
Unimanual Contact	38.81 ± 16.81	42.80 ± 12.16	$t(16) = -1.31$, $p = 0.208$, $d = 0.66$
Bimanual Contact	19.47 ± 13.31	23.28 ± 13.74	$t(16) = -1.76$, $p = 0.097$, $d = 0.88$
Contact with the Non-Preferred Hand	17.04 ± 9.40	23.11 ± 8.18	$t(16) = -4.26$, $\mathbf{p < 0.001}$, $d = 2.13$
Manipulation with the Non-Preferred Hand	7.86 ± 8.66	12.84 ± 8.96	$t(16) = -3.09$, $\mathbf{p = 0.007}$, $d = 1.55$
Strength of Hand Preference for Object Contact	3.71 ± 1.77	3.48 ± 1.35	$t(16) = 0.67$, $p = 0.512$, $d = 0.34$
Strength of Hand Preference for Object Manipulation	1.54 ± 1.29	1.63 ± 0.85	$t(16) = -0.34$, $p = 0.741$, $d = 0.17$

Note. Statistically significant ($p \leq 0.05$) results are marked in bold.

3.2. The Effect of the Playskin on Children's Hand-Use Preferences (H2)

Reaching Assessment. We observed a significantly higher percentage of non-preferred hand use while wearing the Playskin compared to unassisted reaching (absolute change 5.52, relative change 86.66%, $p = 0.001$; Figure 3B). No difference was observed between the experimental conditions for the strength of hand preference ($p = 0.558$; Figure 4). See Table 1 for statistical parameters.

Object Exploration Assessment. For hand-use preferences, while *contacting objects*, the use of the non-preferred hand was significantly higher while wearing the Playskin compared to testing without the Playskin (absolute change 6.07, relative change 35.62%, $p < 0.001$, see Figure 3B). No difference between the experimental conditions was observed for the strength of hand preference ($p = 0.512$, Figure 4). Similar results were obtained for hand-use preferences while *manipulating objects*: there was a significant increase in the use of the non-preferred hand between the OFF and ON conditions (absolute change 4.98, relative change 63.36%, $p = 0.007$; Figure 3B), while no difference was observed between the conditions for the strength of hand preference ($p = 0.741$; Figure 4). Corresponding statistical parameters are presented in Table 2.

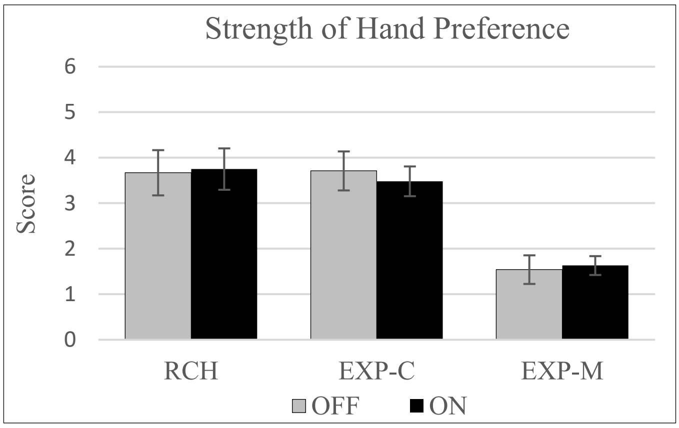

Figure 4. Average (*Mean* ± *SE*) strength of hand preference manifested by children in the OFF and ON experimental conditions; RCH = object contact in the reaching assessment; EXP-C = object contact in the object exploration assessment; EXP-M = object manipulation in the object exploration assessment.

3.3. Relation between Hand-Use Preferences and Quality of Object Exploration (H3)

Reaching Assessment. An increase in the use of the non-preferred hand was associated with more bimanual contact ($p = 0.001$), more bouts of behavior ($p = 0.008$), higher variability of behavior ($p = 0.007$), and more combined behavior ($p = 0.004$), but was not significantly related to children's visual attention ($p = 0.138$). An increase in the strength of hand preference was linked to greater variability of behavior ($p = 0.044$) and performance of combined behaviors ($p = 0.005$) while not correlating with bimanual contact ($p = 0.628$), visual attention ($p = 0.396$), or bouts of behavior ($p = 0.059$). Statistical parameters for these analyses are presented in Table 3.

Table 3. Statistical parameters for bivariate Pearson correlations (two-tailed) relating children's hand-use preferences to the quality of their object exploration.

Variables	Contact with the Non-Preferred Hand	Strength of Hand Preference in Object Contact
	Reaching	
Bimanual Contact	$r(15) = 0.71$, $\mathbf{p = 0.001}$	$r(15) = 0.13$, $p = 0.628$
Visual Attention	$r(15) = 0.38$, $p = 0.138$	$r(15) = 0.22$, $p = 0.396$
Bouts of Behavior	$r(15) = 0.62$, $\mathbf{p = 0.008}$	$r(15) = 0.47$, $p = 0.059$
Variability of Behavior	$r(15) = 0.63$, $\mathbf{p = 0.007}$	$r(15) = 0.49$, $\mathbf{p = 0.044}$
Combined Behavior	$r(15) = 0.66$, $\mathbf{p = 0.004}$	$r(15) = 0.64$, $\mathbf{p = 0.005}$
	Object Exploration	
Bimanual Contact	$r(15) = 0.05$, $p = 0.841$	$r(15) = -0.07$, $p = 0.802$
Visual Attention	$r(15) = -0.12$, $p = 0.657$	$r(15) = 0.003$, $p = 0.990$
Bouts of Behavior	$r(15) = 0.70$, $\mathbf{p = 0.002}$	$r(15) = -0.11$, $p = 0.689$
Variability of Behavior	$r(15) = 0.18$, $p = 0.496$	$r(15) = 0.08$, $p = 0.747$
Combined Behavior	$r(15) = 0.41$, $p = 0.103$	$r(15) = 0.09$, $p = 0.718$

Note. Statistically significant ($p \leq 0.05$) results are marked in bold.

Object Exploration Assessment. An increase in the use of the non-preferred hand was significantly correlated with more bouts of behavior ($p = 0.002$) but was not associated with bimanual contact ($p = 0.841$), visual attention ($p = 0.657$), variability of behavior ($p = 0.496$), or combined behaviors ($p = 0.103$). Moreover, the strength of hand preference did not significantly correlate with bimanual contact ($p = 0.802$), visual attention ($p = 0.990$), bouts of behavior ($p = 0.689$), behavioral variability ($p = 0.747$), or combined behaviors ($p = 0.718$). See Table 3 for corresponding statistical parameters.

4. Discussion

The primary aim of this study was to investigate whether environmental affordances would influence demonstrated early hand-use "preferences" in children with muscular weakness and motor impairments.

4.1. The Effect of the Playskin on Children's Reaching and Object Exploration Ability (H1)

The current results provided partial support for our first hypothesis, **H1**. We expected that the Playskin exoskeletal garment, which offers anti-gravity support for the arms, would increase children's right-handed, left-handed, and bimanual contact with objects. In the reaching assessment, Playskin use led to a significant increase in right-handed (31.23%), unimanual (24.67%), and bimanual (32.33%) contact without noticeable differences in left-handed contact. In the object exploration assessment, no significant differences were found between the two experimental conditions (OFF vs. ON) across any type of object contact. Thus, we concluded that anti-gravity support, in general, might increase children's unimanual and bimanual hand use in certain tasks. Similar results were obtained by previous research with children born preterm or diagnosed with arthrogryposis [97]. However, the current results also suggested that the impact of providing upper extremity assistance may vary across tasks. Similarly, previous research showed that displayed hand preferences might depend on the nature of the task (e.g., unimanual vs. bimanual [104]), skill level required (e.g., skilled vs. unskilled tasks, complex vs. easy tasks [105–107]), location of the presented object (e.g., left-space vs. right-space, midline position vs. contralateral space [72,104–106,108]), the number of object presentations (e.g., 9 vs. 32 [109], and the object type (e.g., tool vs. dowel [105]).

4.2. The Effect of the Playskin on Children's Hand-Use Preferences (H2)

The current data partially supported our second hypothesis, **H2**. We expected a significant increase in the use of the non-preferred hand and a decrease in the strength of children's hand-use preference for object contact and manipulation while wearing the Playskin. For both assessments, wearing the Playskin resulted in a significant increase in the percentage of non-preferred hand use: 86.66% for object contact in the reaching assessment, and 35.62% and 63.36% for object contact and object manipulation, respectively, in the object exploration assessment. Interestingly, during the testing procedures, we observed that the hand-use "preference" of children changed considerably within minutes while using the Playskin. A significant increase in the use of the "non-preferred" hand in response to the enhanced environmental affordances (i.e., anti-gravity support for the arms) might suggest a malleable nature of the hand-use "preference" in children with arthrogryposis at this age. Such extreme plasticity of the "hand preference" supported our notion that manual lateralization of children with motor impairments is not a manifestation of their "*preference*" per se, but rather, is an indication of their lacking affordances: due to muscle weakness and joint contractures, children with arthrogryposis just cannot "*afford*" the use of both hands. In this case, the enhancement of environmental affordances changed children's inherent affordances and, consequently, their abilities.

Furthermore, we found no difference in the strength of hand preference between the two experimental conditions for both assessments. These results might be explained by the very strong positive correlation between the time contacting objects with the non-preferred hand and the time contacting objects bimanually. It appears that anti-gravity support for the arms not only promoted children's use of the non-preferred hand but also allowed greater synchrony between the hands, which translated into more bimanual activity. However, if actions performed by the non-preferred hand were coupled with the actions by the other hand, they were coded as bimanual actions and not unimanual ones. This might explain the apparent lack of change in the strength of manual lateralization coexisting with a significant change in the use of the non-preferred hand.

4.3. Relation between Hand-Use Preferences and Quality of Object Exploration (H3)

The current results also provided partial support for our third hypothesis, **H3**. We expected that children's use of the non-preferred hand and the strength of their hand-use preference would be significantly correlated with the quality of their play manifested in bimanual exploration, visual attention to objects, as well as intensity, variability, and complexity of object exploration. For the reaching assessment, an increase in the use of the non-preferred hand was significantly associated with greater bimanual exploration and behavioral intensity, variability, and complexity, while it was not linked to changes in visual attention to objects. On the other hand, the strength of hand preference was associated with higher variability and complexity of behaviors but not with bimanual exploration, visual attention, or behavioral intensity.

For the object exploration assessment, an increase in the use of the non-preferred hand was associated with greater behavioral intensity but was not linked to other behaviors. Similarly, the strength of hand preference did not significantly correlate with any of the behaviors assessed. Again, it looks like the effect of hand-use preference on play quality might depend on the assessment used. Also, it might be the case that an increase in object interactions with the non-preferred hand indirectly affects behavioral intensity, variability, and complexity through an increase in bimanual exploration, but the current small sample would not allow testing this assumption. In any case, whether we assume a direct or indirect relation between an increase in the use of the non-preferred hand and the quality of children's play, this relation highlights the importance of manual lateralization (i.e., a lack of it) for object exploration.

Previous research showed that coupling of the hands for bimanual contact is significantly associated with the emergence of complex role-differentiated bimanual object manipulation [21], whereas sophisticated object exploration advances children's cognitive development [95,110–113]. Taking those findings into account, it is not hard to envision how changes in manual lateralization may affect the future cognitive development of children.

4.4. Conclusions, Limitations, and Future Directions

The current results suggested that providing anti-gravity support for children's arms might enhance their ability to reach and interact with objects in both a unimanual and bimanual manner. However, the magnitude of this enhancement may depend on the testing procedure implemented. For example, we found significant differences in children's unimanual and bimanual play with objects in a more structured reaching assessment but not in a less structured object exploration assessment in which toys were placed on the floor instead of being presented one by one in front of the child.

Furthermore, the external support provided to the children's arms by the Playskin Lift^{TM} exoskeletal garment was found to promote the use of the non-preferred hand for object contact and object manipulation. *Thus, it is likely that children with impaired upper extremity functioning do not "prefer" to use a particular hand; rather, they cannot afford using both hands due to their limited muscular or manual abilities.* External, anti-gravity assistance for children's arms seems to encourage a more balanced use of both hands, thus facilitating the development of enriched bimanual object exploration and manipulation.

To our knowledge, this is the first study to explore the effect of environmental affordances on manifested hand-use preferences in children with arthrogryposis. Although previous research has explored more extensively changes in hand use as a result of interventions in children with cerebral palsy or children after a stroke, those studies mainly focused on the functioning of the affected hand or bimanual functioning but not on the hand-use preference or manual lateralization per se, e.g., [61,63,86,114,115].

One of the limitations of this study was determining a child's non-preferred hand using the HPI score at each visit. Some previous research suggested that hand-use preferences may be more accurately determined through latent class trajectories showing the development of hand preferences across time [101]. However, implementing this technique would require a very large sample of data, which was not feasible for this study. Also, other researchers evaluated the reliability of handedness classification based on individual sessions vs. developmental trajectories and concluded that the *direction* of hand preference (i.e., right vs. left) can be reliably identified based on individual sessions [116].

Furthermore, although some might argue that bimanual actions are an important part of children's manual repertoire and should be accounted for while determining lateral hand use, HPI scores in this study were calculated without considering bimanual actions. We believe that bimanual actions provide insights into the symmetry of hand use rather than its lateralization [117]. Also, previous research showed that the inclusion of bimanual actions does not significantly affect the hand-preference classification [101].

Although trunk stability and movement were beyond the scope of this study, previous research suggested a significant effect of postural control on reaching abilities and patterns during early childhood [47,118]. This issue is especially important because children with arthrogryposis use their trunks to facilitate manual functioning. Note that the use of the Playskin was associated with a significant decrease in compensatory trunk "flinging" to facilitate reaching in children with arthrogryposis [80]. It is likely that anti-gravity support provided by the Playskin not only improves children's manual functioning during unassisted reaching but also eliminates the need for postural compensation to enable reaching. The resulting reduction in postural flinging increases children's postural stability, thus further improving the development of their reaching skills. Future research should test these assumptions.

Finally, a modest sample size could be noted as a limitation of this study. Nonetheless, the significant findings from this exploratory study underscore the importance of conducting further research in this area using larger samples of children with diverse types of motor delays and impairments.

4.5. Clinical Implications

The current results showed that the Playskin Lift^{TM} soft exoskeletal garment has the potential to increase unimanual and bimanual object interaction, as well as decrease an atypical, exaggerated hand-use "preference" in children with arthrogryposis. Prior research suggested that this device may be used along with targeted intervention activities in the natural environment to improve function when the device is worn [97]. Importantly, the use of Playskin in intervention activities was shown to improve strength and independent functional performance for children with arthrogryposis both during and after a 4-month daily intervention period. This is likely because the Playskin provides support for movement but does not passively move a child's arm through space. Consequently, it offers opportunities for learning, strengthening, and improving function that can result in carry-over effects [97]. It is important to note that the Playskin soft exoskeleton was designed for young children through 3 years of age; by design, the anti-gravity support of the Playskin cannot function for the heavier and longer arms of older children [99]. Thus, the clinical niche of the Playskin is for *early* rehabilitation to support the development of children's manual abilities.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/sym15122161/s1, Figure S1: Average (Mean ± SE) percent time contacting objects with the right hand (A), with the left hand (B), unimanually (C), bimanually (D), and with the non-preferred hand (E), as well as the strength of hand preference (F) manifested by children during the ***reaching assessment*** according to the experimental condition (OFF vs. ON) and the object presentation level (hip, chest, or eye level).

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board at the University of Delaware (protocol code 356189, date of approval 20 August 2015).

Informed Consent Statement: Parents of all subjects involved in the study gave their informed consent for the inclusion of their children in the study.

Data Availability Statement: The data supporting the findings of this study are available on request.

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