A preliminary study toward developing a paediatric prehension classification and outcome measurement for upper limb deficiencies

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ABSTRACT

Background and Purpose
This paper presents the first detailed taxonomy for paediatric prehension classification and identifies prevalent grasp instances to contrast objective reference data within child and adult populations.

Method
An observational study was undertaken with six healthy children between 6-10 years of age. Children were filmed completing three upper limb tasks via a head-camera and stand-alone camera. Video data was analysed alongside quantifiable descriptors to obtain both prevalence and breadth of grasp instances.

Results
The taxonomy developed represents the continuum of prehension patterns, alongside an observational account of the forces contributing to the grasps.

Conclusion
This preliminary study has resulted in the development of a detailed taxonomy of paediatric prehension. Further study with a larger, more heterogeneous, group of children is now needed so that the clinical utility of this study can be realised, potentially contributing to the development of paediatric upper limb outcome measures and rehabilitation protocols

Introduction

The human hand is capable of a combination of motions in order to attain functional requirements. Research to quantify these movements originated from Schlesinger (1919) who proposed six key prehensile patterns that summarised human hand versatility. This was later refined by Napier (1956) who categorised these positions into power (spherical, power and extension) and precision (tip, lateral, and tripod) grasps. These definitive classifications however did not acknowledge the transitional nature of the hand and the variations that are needed to manipulate and manage an object.

There is a general consensus that the human hand has between 21-25 degrees of freedom (DOF) for movement (Iberall, 1997; Bullock and Dollar, 2011). Therefore the number of combinations available surpasses the six original patterns presented in the Napier (1956) classification. Iberall (1997) proposed that for an upper limb task, a variety of grasp instance approaches are available, each requiring adaptive forces to ensure grasping and manipulative stability. This showed that Napier's (1956) discrete static hand patterns were not inclusive of the unique postures, forces and motions within dexterous hand movements. The dynamism of human hand manipulation therefore became difficult to quantify, and the research transitioned to focus on the forces applied by the hand to engage with object handling (Landsmeer, 1962). However the complexity of classifying hand movements remained.

Cutkosky (1989) first proposed a taxonomic tree to illustrate a more comprehensive human grasp classification system accessible in a visual format. The tree acknowledged the dynamic nature of hand positions, by demonstrating the transition of increasing dexterity across the system and also the complexity of prehension geometry as the tree descended. More recently Bullock and Dollar (2011) presented a hand manipulation task taxonomy that showed hand patterns and consequential motions, representing the dynamic interaction and capacity of the hand. These classifications and concepts in the research have concentrated solely on adult prehension, and there is currently no comparative taxonomy for paediatric prehension.

Paediatric prehension patterns are dependent on environmental exposure, repetitive motor patterns and neural development. Halverson (1931) documented a progression of hand use in the early years of life that develops from no hand contact, to squeezing, grasping, and then refining this grasp from gross palmar control to forefinger gripping. The addition of finger control for stabilising objects is refined between ages 1-3, at the same time as bimanual action of the hands is developed. It is not until age 3-4 that the elements of in-hand manipulation are developed, and a child is confident in translating, shifting and rotating an object, demonstrating competence in motor function (Exner, 1990a, 1990b).

Olivier et al. (2007) explained there is a critical period between 6-10 years of age in which basic fine motor programmes have been developed, but have not stabilised to adult levels, due to immature interpretations and control mechanisms. These critical years lead to a window of opportunity in which fundamental skills are mastered but are still malleable to specific refinements. This is a key period for children who have an upper limb deficiency as they begin to notice the functional differences between themselves and their peers as well as between their affected and non-affected arm (Ibbotson 2002). Consequently, adherence to therapy can be affected as well as prosthetic or orthotic treatment resulting in unilateral limb usage for all tasks (Wagner et al, 2007). This can lead to restricted function as well as physical issues, such as asymmetrical development of the spine, postural problems, back pain (Broomfield 2009) and overuse syndrome from increased workload for the non-affected arm (Peterson 2011).

In order to assess motor deficiencies in paediatrics, clinicians utilise knowledge of age- appropriate physical normative values, outcome measures, and self-reported limitations. However, there is no current knowledge on how paediatric prehension patterns are different, and what should be expected in a 'normal' population. Evidence exists of contrasting muscular capacity and neuronal responses between children and adults (Dotan et al., 2012; Glenn et al., 2013). In addition, paediatric activities of daily living vary in nature, frequency and technique to that of an adult (Case-Smith and O'Brien, 2009). This is an important distinction, as the application of adult-based research to a paediatric population can have negative effects on the assessment because the unique child developmental phases are not accounted for (Pearson, 2010). The primary causes of paediatric diseases are congenital rather than acquired, as in adults, with the prognosis and functional implications of deficiencies difficult to predict (Camden et al., 2010). Thus, paediatric rehabilitative interventions focus predominantly on optimising function, rather than recovery to a pre-morbid level, leading to differing therapy expectations and motivations between the child and adult populations. Within paediatric upper limb rehabilitation and outcome measurement there has been little recognition of children's activities of daily living and children's unique prehension, yet it is acknowledged that this has a positive influence on a child's use of a prosthetic device (Egermann et al., 2009). Therefore there is a misrepresentation of this patient group and restrictions exist within the application and validity of the prostheses and outcome measures.

The aim of this preliminary study was to identify common prehension patterns within children aged 6-10 years old. The objectives were to:

- Observe and record the breadth of grasp instances used to engage in functional activities and childhood activities (such as play);

- Use findings to develop a paediatric prehension taxonomy.

Methods

The University of Southampton Faculty of Health Sciences Ethics Committee approved the study (ID: 6000).

Participants

Due to the time limitations for the study, a pragmatic approach to recruitment was taken in order to quickly recruit a convenience sample of participants. Posters advertising the study were displayed in the Faculty of Health Sciences at the University of Southampton. Staff and students with children within the age range 6-10 years were invited to contact the researcher for more information about the study. Respondents were informed of the aims of the study and provided with full participant information (one participant information sheet was provided to parents and a separate, simpler information sheet was given to children). All parents provided informed consent and children provided informed assent prior to participation.

Children were excluded from the study if they had a diagnosed motor deficit which could impact on the way they used their hands, a cognitive deficiency that would prevent full comprehension of the tasks or an allergy to the ingredients in Play-Doh™, which would prohibit their full participation in the tasks.

Procedures

Research took place in the participant's home, in order to maximise the child's engagement within a familiar environment and in the presence of family. The participant's parent or guardian was present throughout the assessment.

Head cameras were used to collect data for the study as they provide an 88.7% correlation with gaze directionality (Asteriadis et al., 2010). Bullock et al. (2013) successfully used head cameras in their study of adult prehension patterns to obtain approximately 4,700 grasp transitions per subject and viable data from the participant's workspace to contextualise the grasps within the surrounding environment. This methodology influenced the current study. The participant was asked to wear a wide-view (130°) head-mounted camera (Drift Helmet Camera, Drift-HD720) attached via a child-sized three-band head strap. An additional stand-alone camera (Canon Camcorder, Legria HFR26), was used to achieve three-dimensional access to clarify the prehension patterns, and attached to a tripod to maintain stability of the recording.

The participants were asked to complete three activities: handwriting (Task One); creating a model of a pig out of Play-Doh™ (Task Two); and a self-selected home based upper limb play activity (Task Three). Upper limb rehabilitation protocols from the College of Occupational Therapists (COT) (2006) highlighted the need for unilateral and bilateral training, structured activity, and free play when completing therapy with a prosthesis; this influenced the selection of the chosen activities. No time limit was given for each task, and the activity was allowed to draw to a natural close. In Task Three, the participants were allowed to engage with other family members or peers, if joint participation in the activity was required, however additional people were not directly filmed. Recording started at the beginning of the task, indicated by the participant clapping, and ceased when the participant clapped again to represent finishing the activity. Participants were told that they could ask to stop filming at any time, either temporarily or permanently, with no reason given. All raw data was deleted on completion of the project in-line with the Data Protection Act (2018) requirements for research.

Task Standardisation

Task one

An A4 piece of paper was provided face down, with an A5 box for writing in. The researcher asked the participant to write a brief description of their family and home. Prompt questions, such as "Can you write a bit more about…", "Is there anything else you can tell me about…" were used to encourage ongoing participation in the task. An HB pencil was provided, with the lead facing the participant, next to the paper on their dominant side.

Task two

Participants were asked to make a model of a pig using the Play-Doh™ provided. Instructions were provided both verbally and in writing. Participants were given four closed pots of Play-Doh™ lined up in order of: pink, orange, black and white. An HB pencil was placed with the lead facing the participant next to the Play-Doh™ lined up on the contralateral side to their dominant hand.

Task three

This was not standardised due to the self-selected nature of the activities.

Data Analysis

To analyse the data, the files were integrated to produce a multi-camera view of the video (Figure 1) using Final Cut Pro (Version 7.0.3). Time points were synced according to the beginning and end participant claps. Prehension patterns that lasted for more than one second (as suggested by Asteriadis et al., 2010) and resulted in at least three DOF (as identified by the researcher), were recorded alongside the time code on the stand-alone camera. A DOF was categorised when a grasp instance had an observable change in flexion/extension or abduction/adduction within the compass of the hand, with no minimal threshold of movement value set. Directional forces applied by the grasp instance were visually interpreted by the researcher and only the dominant hand was analysed. Definitions and classifications are detailed in Table 2.

Figure 1: A multi-camera video frame still demonstrated from a participant

Descriptive Classification

Descriptive categories were developed based on the observed trends during data collection and influences of previously established adult prehension classifications (Napier, 1956; Landsmeer, 1962; Iberall, 1997).

Statistical Analysis

The primary objective of this study was to observe the cumulative presentation of the most common grasp instances across tasks in order to develop a paediatric prehension taxonomy. Each grasp instance was sorted alongside the classifying descriptors and allocated several categories, if a combination of patterns were demonstrated. The frequency of each classification combination was calculated to develop the taxonomy. Comparable features of the prehension patterns were observed and the taxonomy utilised video data of the hand to represent the variety of postures demonstrated.

Secondary observations were conducted on each classifying descriptor. An index of usage was calculated by summing the frequency for each descriptor, both for each individual task and across all three tasks, and dividing it by total prevalence recorded. Classifications were therefore relatively normalised so any bias of prehension patterns demonstrated (e.g. tripod in the handwriting task) were accounted for.

The Vectors and Supplementary Digits descriptors were further analysed across age ranges. For parametric tests, a one-way analysis of variance (ANOVA) was used to determine if there were significant differences between (i) relative vector prevalence (to account for the varying number of grasp instances between participants) and age range; (ii) relative supplementary digit prevalence and age range. For non-parametric data, a Kruskal-Wallis test (Vincent, 2005) was conducted to observe significant differences.

Statistical analysis was performed using SPSS version 21.0 and significance level was set at $p \leq 0.05$. Post-hoc power calculations were not feasible due to one group (age 10) having less than 2 cases, but differences were observed in mean plot graphs.

Results

Demographics

Six children (6 females, 5 right-handed, 1 left-handed) between the ages of 6-10 (mean ± SD, 8 ± 1 years) were recruited to participate in the study and completed all three activities. Data from all six children has been included in the analysis. Table 1 provides participant demographics and their respective choices for Task Three.

Participant	Age	Gender	Hand Dominance	Task Three Activity
1	8	F	R	Throwing/catching balls
2	7	F	R	Playing the ukulele
3	7	F	R	Arts and crafts
4	10	F	R	Playing the X-Box™
5	8	F	L	Playing on PC Computer
6	7	F	R	Playing with dolls

Table 1: Participant demographics of the prehension study (F = Female; L= Left; R = Right)

Hand Patterns Demonstrated from Video data

Over 1200 grasp instances were recorded from 93 minutes of video data. The classification of grasp instances was completed by one observer alongside the descriptors in Table 2. The variety of postures recorded were: 76% prehension patterns (Average DOF = 14 ± 2), 15% non-prehension patterns (Average DOF = 9 ± 5), 9% involved no contact (Average DOF = 12 ± 3) and 0.16% were ½ prehension/ ½ non-prehension patterns (Average DOF = 15 ± 1). These were rounded to the nearest whole number. The dominant hand was the acting hand within the tasks for 86% of postures, and stabilising for 14% of activities.

Classifying Descriptor	**Code**	**Explanation**	
Prehension pattern	PP	Object seized and held partly or wholly in the compass of the hand	
Non-prehension pattern	NP	Seizing does not occur but the whole hand or finger applies pressure on the object *(Landsmeer 1962)*	
Acting hand	A	Dominant hand analysed is manipulating the object in the task	
Stabilising hand	S	Dominant hand analysed is stabilising the object in the task	
			Comparable Napier (1956) Descriptor
Precision grip (Fingers involved recorded after code)	PrecP	Palmar pads of involved fingers used to sustain the grip	Tip
	PrecL	Palmar thumb and lateral edge of fingers used to sustain the grip (or vice versa)	Lateral
	PrecT	Combination of palmar and lateral contacts demonstrated in the grip	Tripod
Power grasp (Fingers involved record after code)	PowO	Power originating from the palm with no palm contact	Extension
	PowC	Power originating from the palm with palm contact	Power/ Spherical
	Hook	Power originating from the length of the fingers, with no thumb or palmar contact.	
Vectors	-	A finger or collection of fingers that provide an oppositional force to the object in a different direction (Iberall, 1997)	
Supplementary Digits *(Fingers involved recorded after the code)*	R( )	Reinforced fingers involved in the prehension pattern. The number in brackets signifies the digit that is being strengthened.	
	A	Fingers either not involved or abducted away from prehension pattern	
Degrees of Freedom (DOF)		From the 22 DOFs categorised for the hand and wrist, the average number of involved motions recorded with each hand posture.	

Non-contact	NC	Dominant hand analysed is not in contact with an object but still demonstrating a hand posture.

Table 2: Classifying descriptors, allocated codes and their definitions in the prehension study

Paediatric Prehension Taxonomy

Across the three tasks, 127 unique classifications were identified across precision/power postures, vectors and supplementary digits. Any combination prehension pattern that was demonstrated 3 or more times was included in the development of the taxonomy. The frequency of the sub-division precision/power descriptors were: PrecP (21.5%), PrecL (11.5%), PrecT (34.2%), PowO (19.8%), PowC (11.5%) and Hook (1.5%) (see table 2 for explanations of each descriptor). In addition, the participants demonstrated 18 combinatory postures (1.5%) that represented variations of both precision and power classifications.

The taxonomy (Figure 2) initially divides between contact and non-contact postures. It is further sub-divided into prehensile and non-prehensile contact with the object. The prehension patterns have then been further developed down the taxonomy tree to differentiate between strength originating from the fingers (precision and hook postures) and the palm (PowO/PowC postures).

Common themes across these precision and power prehension patterns included postures with the fingers abducted away, fingers used to reinforce postures, and the combination of the two, which then gave the descending sub-division. The number of vectors recorded for each division was classified within the partition to illustrate the range of forces demonstrated.

The taxonomy is organised from left to right based on the increase in strength that is required from each grasp instance.

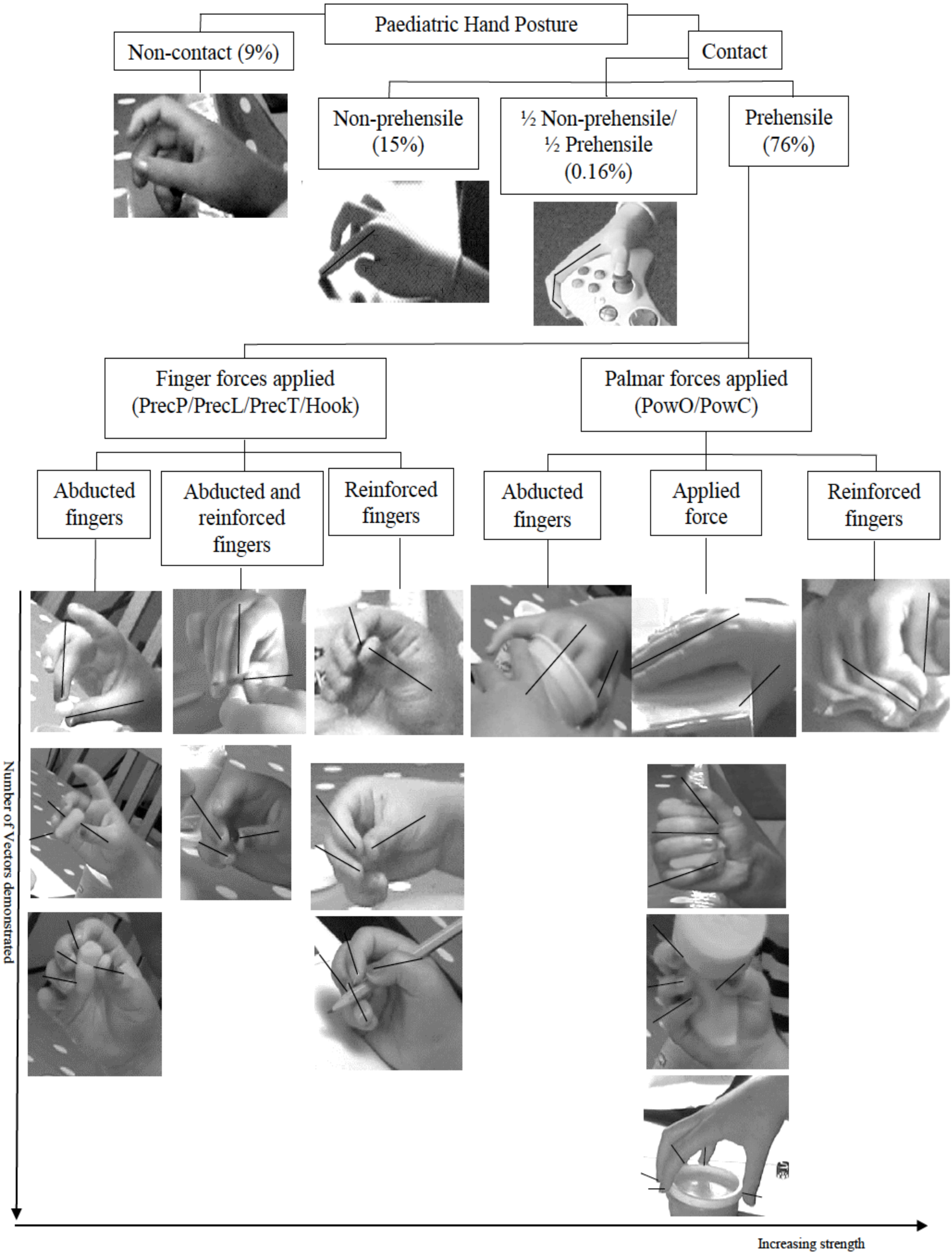

Figure 2: A Paediatric Hand Posture Taxonomy (lines on the pictures represent the contributing vector forces)

Classifying Descriptor's Prevalence

All descriptors are classified with each finger correlated with a number (i.e. thumb = 1; index finger = 2 etc.). Percentage prevalence is stated in brackets after the descriptors.

Precision/Power Descriptor

Precision/Power descriptors were classified according to the origin of the controlling forces (fingers or from the palm). Contributing fingers are listed after the descriptor. Across the three tasks, the five most commonly demonstrated precision/power postures were: PowO (20%), PrecT123 (17%), PrecT1234 (13%), PowC (11%) and PrecP123 (8%). There were 21 additional categories recorded in this descriptor.

Vectors Descriptor

The Vector descriptors used dashes between numbers to indicate a different directional force to the previous finger(s), for example 1-2-3 would equate to an adult tripod grip in Napier's classification (see Table 2 for more details). The five most common vector combinations were: 1-2-3 (18%), 1-2 (14%), 1-23 (12%), 1-23-4 (8%) and 1-234-5 (6%), correlating well with some of the precision/power descriptors. An additional 30 combinations were categorised.

Supplementary Digits Descriptor

The Supplementary Digits descriptor utilised the notations 'A' for fingers that were abducted away from the grasp instance, and 'R' for digits that reinforced prehension patterns. Supplementary digits prevalence was: R(3)45 (18%), A45 (17%), R(4)5 (17%), A5 (12%) and A345 (10%), with another 23 combinations recorded.

Discussion

For 86% of the tasks, the participant's dominant hand predominantly interacted with objects, demonstrating the functional requirement for bilateral arm use. In children with an upper limb amputation or unilateral upper limb deficiency, bimanual hand use is delayed (Thornby and Krebs, 1992), highlighting the importance of appropriate therapeutic intervention.

The 9% observation of non-contact postures reinforces previous work about anticipatory control in children. Duff and Charles (2004) explained that during prehension development in childhood, there is a pre-shaping of the hand to the object and the grading of fingertip forces as a neuro-motor strategy that aims to reduce movement variability. This was observed in the current study, with the average DOF recorded as 12 ± 3, with the fingers commonly in a semi-flexed and abducted position, anticipating the hand prehension requirements for the next part of the task. Therefore emphasis and practice of these early motor schemas should not be overlooked, but incorporated into rehabilitation interventions for children with upper-limb deficiency.

The most limited grasp instances were demonstrated playing with the X-Box™ and on a Personal Computer (1 posture each). In both cases the grasp instances recorded had multiple components, and were allocated a ½ prehension and ½ non-prehension category. No previous studies have categorised in this manner. Despite the limited occurrence, these grasp instances should be recognised, as engagement with technologies is becoming a core component of both functional and self-motivated activities in children (Livingstone, 2002). In the current study, technology use was self-selected and represented several activities that could be considered childhood activities.

Existing research in adult prehension patterns states that it is the shape and size of the object, and the task to be performed, that determines the prehensile pattern that leads to combined prehension patterns (Napier, 1956). In the current study the paediatric participants demonstrated 18 combined patterns (1.5% of postures recorded). The prevalence of combinatory/'intermediate' postures was recorded as

14% in one study of seven adults (Kamakura et al., 1980); however no definition was given to differentiate the terminology of this classification. The role and importance of combination patterns is unknown at present and is no longer discussed in current prehension research. It may be that, due to access to comparative theories in adult prehension literature, the historic researchers were more definitive categorising grasp instances and this nomenclature became obsolete. Due to the novel approach to paediatric classification in the current study, acknowledging the dynamism and forces applied by the hand, the combined categories remained to encompass the spectrum of observed patterns.

Sollerman (1980) identified eight common grasp instances demonstrated in adult activities of daily living, and their prevalence in these occupations. There is no current comparative data within the child population, due to assumptions of similar prehension patterns and engaging occupations. Through this current study, initial data has been presented to illustrate the prevalence of certain patterns, with the Hook being least popular (1.5%) and PrecT (representing a tripod posture) being most popular (34.2%). The frequency of this posture is not only related to the handwriting task, but also represents the most prevalent prehension patterns used to manipulate the Play-Doh™. The bias of longer data sets and increased prehension prevalence were accounted for in the statistical analysis to make the participants comparable, therefore any task or participant bias was reduced. The frequency of PrecT contrasts with the 10% prevalence of the tripod pinch in the Sollerman study, highlighting that there are differences in the prominence of various prehension patterns between children and adults.

This feasibility study has provided important research concerning the breadth of paediatric prehension patterns and frequency; however limitations in the sampling gender and number restrict the generalizability of the findings. It should be noted that previous research found that females (aged 5-12 years old) used more complex grasping patterns, recruited more digits and had more flexible fingers than males (Wong and Whishaw, 2004). Therefore, despite not encompassing both genders, the taxonomy may still suitably represent a large breadth of the prehension patterns that are used by children. The limited age range of the participants also did not represent the target age range of the current study. However the prehension differences noticed in the omitted ages would have been observed in grip forces, latency time and coordination and not necessarily the specific hand posture itself (Olivier et al., 2007). Therefore, further research on a larger scale is needed to apply these theories to a wider population.

The tasks selected aimed to encompass the spectrum of activities that children engage in during daily activity and elicit a variety of manipulation skills. Sims et al. (2013) discussed the desired roles of paediatric upper limb prostheses with children age 8-15 who had a correlating impairment. These children reported the necessity of prostheses for competence in functional (writing, typing, cleaning), play, and sporting activities to help levels of social engagement at home and with peers. Consequently, tasks in these three dimensions were incorporated alongside the recommended UK's COT (2006) therapy structure. This approach contrasts the functional bias of the fairly narrow paediatric and adult upper limb tasks selected in outcome measures that are currently used to evaluate these deficiencies (Aslam et al., 2015; Metcalf et al., 2007). Despite these functional assessments presenting moderate reliability, it was important in the current study to reflect prosthetic rehabilitation protocols and the motivations of the child and therefore non-validated tasks were selected.

The production of the taxonomy aims to incorporate the breadth of patterns demonstrated and represent strength variations in children, however it does not discuss the specific manipulations of fingers represented at lower-levels of the classification. Gaps in the current taxonomy resulted from the small sample size and task selection in this feasibility study. Therefore this research would benefit from a broader, in-depth study, which may help to identify gaps and develop more 'branches' in the current taxonomy. For future research, the handwriting task could be adjusted to improve participant motivation through play-based exercises such 'join-the-dots' or 'mazes'. This may reduce the formality of this assessment and potentially demonstrate more varied manipulations. An increased number of tasks that would allow the child to demonstrate a wider variety of prehension skills, including an activity with a technology bias, would prove beneficial to improve this breadth further.

Videotaping children in research has become more popular, due to the objective quantification and ongoing access to data that was limited by other record keeping or parental observation approaches (Auyeung et al., 2006). Bullock et al. (2013) most recently employed the use of a head camera to obtain unobtrusive footage to observe the quantity of grip to grasp transitions in adult manual work (machinists and house cleaners). The design of that study influenced the current approach. The use of two cameras in this current study provided three-dimensional access to prehension patterns and the participant's viewpoint.

Proximity limitations were occasionally observed with the head camera, due to the comparative shorter torso of the paediatric participants and techniques using the hands close to the face, meaning there was a small viewing angle of the hands. The use of two cameras in this instance allowed the researchers to clarify patterns and allowed wider-angle viewing of specific manipulations, improving access to valid data. A large amount of detailed information was obtained via this novel methodology, with motivating and engaging behaviours observed from the participants. Therefore this methodology shows suitable potential for unobtrusively observing children for future research.

The current classification was categorised by the visual interpretation of one researcher. To enable the application of the taxonomy to clinical practice, a larger-scale study with a more heterogeneous group of children is needed before further work to establish intra- and inter-rater reliability is carried out. Furthermore, it should be acknowledged that taxonomies visually represent a discrete classification of a spectrum of prehension activities that change with task demands. Therefore the taxonomy should be used as a reference point, but not as a sole assessment tool. This supports Aslam et al's (2015) view that assessment tools should be combined to provide a thorough overview of a child's hand and upper limb functioning.

This is the first observational study that has aimed to quantify paediatric prehension patterns and develop a paediatric taxonomy for clinical use. Previous work has assumed that adult and child prehension is the same and this is applied across paediatric rehabilitative strategies. With further development, the proposed classification may help to tailor interventions directly to the paediatric patient, through acknowledgment of differing hand combinations in this population. Particular areas of theoretical and practical application of this research may be within the domains of paediatric upper limb outcome measures and prosthesis design. However further research should be conducted on a larger scale, and with a more diverse participant group, to refine the taxonomy and generalise its application to a wider paediatric population.

References

Aslam R., van Bommel, A., Southwood, T., Hackett, J. & Jester A. (2015). An evaluation of paediatric hand and upper limb assessment tools within the framework of the World Health Organisation International Classification of Disability, Functioning and Health. Hand Therapy, 20(1), 24–34.

Asteriadis, S., Karpouzis, K., & Kollias, S. (2010) Head pose estimation with one camera, in uncalibrated environments. Proceedings of the International IUI 2010 Workshop on Eye Gaze in Intelligent Human Machine Interaction, February 7-10 2010, Hong-Kong, China.

Auyeung, W., Canales, R. A., Beamer, P., Ferguson, A.C., Leckie, J.O. (2006) Young children's hand contact activities: An observational study via videotaping in primarily outdoor residential settings. Journal of Exposure Science and Environmental Epidemiology, 16, 434-446.

Broomfield M (2009) Guide to Artificial Limbs. Tavistock, Devon: Reach Charity Ltd.

Bullock, I. M., & Dollar, A. M. (2011). Classifying human manipulation behaviour. Proceedings of the IEEE International Conference on Rehabilitation Robotics, 27 June – 1 July 2011, Zurich, Switzerland, 508-513.

Bullock, I. M., Zheng, J. Z., De La Rosa, S., Guertler, C., & Dollar, A. M. (2013) Grasp frequency and usage in daily household and machine shop tasks. IEEE Transactions on Haptics, 6(3), 296-308.

Camden, C., Tétreault, S., & Swaine, B. (2010) Rehabilitation for children – How is it different from rehabilitation for adults? In: Stone, J. H., & Blouin, M. (Eds.), International Encyclopedia of Rehabilitation. Available at: http://cirrie.buffalo.edu/encyclopedia/en/article/274/ (accessed 25 July 2018).

Case-Smith, J. & O'Brien, J. C. (2009). Occupational Therapy for Children (6th edition). London, Mosby.

College of Occupational Therapists. (2006). Upper limb Prosthetic Rehabilitation (Guidance). London, UK: COT UK.

Cutkosky, M. R. (1989). On grasp choice, grasp models, and the design of hands for manufacturing tasks. IEEE Transactions on Robotics and Automation, 5(3), 269-279.

Dotan, R., Mitchell, C., Cohen, R., Klentrou, P., Gabriel, D., & Falk, B. (2012). Child-adult differences in muscle activation – A review. Pediatric Exercise Science, 24(1), 2-21.

Duff, S. V., & Charles, J. (2004) Enhancing prehension in infants and children: Fostering neuromotor strategies. Physical and Occupational Therapy in Pediatrics, 24(1-2), 129-172.

Egermann M., Kasten P. and Thomsen M. (2009). Myoelectric hand prostheses in very young children. International Orthopaedics 33(4): 1101-1105.

Exner, C. E. (1990a). In-hand manipulation skills in normal young children: A pilot study. Occupational Therapy Practice, 1, 63-72.

Exner, C. E. (1990b). The zone of proximal development in in-hand manipulation skills of non-dysfunctional 3- and 4-year old children. American journal of Occupational Therapy, 44, 884-891.

Glenn, N. M., Knight, C. J., Holt, N. L., & Spence, J. C. (2013). Meanings of play among children. Childhood, 20(2), 185-199.

Great Britain (2018). Data Protection Act. London: Stationery Office.

Halverson, H. M. (1931). An experimental study of prehension in infants by means of systematic cinema records. Genetic Psychology Monographs, 10, 107-284.

Ibbotson, V. (2002). Upper limb amputees and limb-deficient children. In: Turner A, Foster M and Johnson S (eds.) Occupational therapy and physical dysfunction – principles, skills and practice (5th edition). London, Elsevier, pp. 379-393.

Iberall, T. (1997). Human prehension and dextrous robot hands. The International Journal of Robotics Research, 16(3), 285-299.

Kamakura, N., Matsuo, M., Ishii, H., Mitsuboshi, F., & Miura, Y. (1980). Patterns of static prehension in normal hands. The American Journal of Occupational Therapy, 34(7), 437- 445.

Landsmeer, J. M. F. (1962). Power grip and precision handling. Annals of Rheumatology Disorders, 21(2), 164-170.

Livingstone, S. (2002). Children's use of the internet: A review of the research. London, UK: National Children's Bureau.

Metcalf, C., Adams, J., Burridge, J., Yule, V. & Chappell, P. (2007). A review of clinical upper limb assessments within the framework of the WHO ICF. Musculoskeletal Care, 5(3), 160–173.

Napier, J. R. (1956). The prehensile movements of the human hand. The Journal of Bone and Joint Surgery, 38B(4), 902-913.

Olivier, I., Hay, L., Bard, C., & Fleury, M. (2007). Age-related differences in the reaching and grasping coordination in children: Unimanual and bimanual tasks. Experimental Brain Research, 179, 17-27.

Pearson, G. D. (2010) Avoiding 'hand-me-down' research: The importance of pediatric studies. Proceedings of the American Academy of Pediatrics National Conference and Exhibition, 1-5 October 2010, San Francisco, California.

Peterson, J. (2011). The Prosthetic Habilitation of a Congenital, Transradial Limb Deficient Child, A Case Study Analyzing the Functional Effectiveness and the Benefits of Early Prosthetic Fitting, Appropriate Prosthetic Equipment, and Consistent Caregiver Follow up. MEC 11 Raising the Standard, Proceedings of the 2011 MyoElectric Controls/Powered Prosthetics Symposium Fredericton, New Brunswick, Canada.

Schlesinger, G. (1919). Der mechanische aufbau der kunstlichen glieder [The mechanical design of artificial limbs). In M. Borchardt (Ed.), Ersatzglieder und arbeitshilfen füir kriegsbeschäidigte und unfallverletzte [Spare parts and tools for war-damaged and accident-injured] (pp.321-661). Berlin, Germany: Springer-Verlag.

Sims, T., Donovan-Hall, M., & Metcalf, C. (2013) Exploring the views of children and parents to contribute towards the development of upper limb prostheses. Proceedings of the International Society for Prosthetics and Orthotics, 4-7 February 2013, Hyderabad, India.

Sollerman, C. (1980). In Handens greppfunktion: analys och utvärdering samt en ny testmetod [In Handen's grip function: analysis and evaluation as well as a new test method]. PhD Thesis, University of Göteborg, Sweden.

Thornby, M. A., & Krebs, D. E. (1992). Bimanual skill development in pediatric below-elbow amputation: A multi-centre, cross-sectional study. Archives of Physical Medicine and Rehabilitation, 73, 697-702.

Vincent, W. J. (2005). Statistics in Kinesiology. Champaign, IL, USA: Human Kinetics.

Wagner, L.V., Bagley, A.M. and James, M.A. (2007). Reasons for prosthetic rejection by children with unilateral congenital transverse forearm total deficiency. Journal of Prosthetics and Orthotics, 19(2), 51-54.

Wong, Y.J., and Whishaw, I. Q. (2004). Precision grasps of children and young and old adults: Individual differences in digit contact strategy, purchase pattern, and digit posture. Behavioural Brain Research, 154(1), 113-123.