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Scoring People With Spinal Muscular Atrophy on the Motor Function Measure Using the Microsoft Kinect

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Purpose: Assess the ability of the Kinect to capture movement and posture of people with spinal muscular atrophy (SMA) during completion of 14 items of the Motor Function Measure, a validated functional rating scale for people with neuromuscular diseases.

Methods: Multicenter feasibility study in which Motor Function Measure items were scored as usual by the participant's therapist during the completion (Score-T) while another therapist scored items based only on the visualization of digital data collected using the Kinect (Score-D). Agreement and disagreement were investigated.

Results: Twenty people with SMA type 2 or 3 were participants; 142 items were recorded and analyzed. There was 31.7% agreement between Score-T and Score-D for participants with SMA type 2, and 76.2% for those with SMA type 3.

Conclusions: The results prevent us from considering the use of Kinect capture to deduce an automated scoring, but this device may be of interest to highlight potential compensations. (Pediatr Phys Ther 2022;000:1–6)

Key words: data display, motor function, outcome assessment, spinal muscular atrophies of childhood, task performance and analysis

INTRODUCTION

Spinal muscular atrophy (SMA) is an inherited autosomal recessive neuromuscular disorder caused by a homozygous absence or loss of function mutation of the *SMN1* gene.¹ It is characterized by the degeneration of motor neurons of the anterior horn of the spinal cord, resulting in muscle weakness according to the age and stage of motor development acquired at the onset of the disease.^{2–4} Authors have defined different types of SMA according to the ability of affected people to sit or walk; those with type 1 do not acquire autonomous sitting position, those with type 2 do not acquire independent walking, and those with type 3 have difficulty running, climbing stairs, or getting up from a chair.

With the advancements in molecular genetics and the better understanding of the pathogenesis and natural history of SMA, new therapeutic approaches have been developed and approved by the Food and Drug Administration and the European Medicines Agency.^{5–7} To evaluate the effects of therapeutics

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on people, valid and sensitive assessment tools are needed. In SMA, the Motor Function Measure (MFM)^{8,9} is a validated tool that is reliable and sensitive to change^{10,11} and has been used as a primary outcome measure in clinical trials or observational studies (eg, study ClinicalTrials.gov numbers: NCT02628743, NCT00774423, NCT02908685).

Training of therapists in MFM completion is essential and maintains good to excellent interrater reproducibility for all items^{8,9}; however, despite standardized MFM training sessions, there is interrater variability in the item-scoring procedure. This is mainly dependent on the intrinsic qualities of the participants and therapists such as mood or motivation. These factors are difficult to control.¹²

The use of easy-to-use markerless motion capture and analysis technologies could be a method to enhance MFM reliability. Use of motion capture technology may allow the completion of a functional rating scale such as the MFM in a playful environment that could promote optimal participation from participants. It could also provide automatic item scores based on digital data from capture of participant movements.

Among the many sensors available in video games, the optical sensor system Kinect (Microsoft, Redmond, Washington) provides good representation of human kinematics¹³⁻¹⁹ and has potential to be used for completion of MFM. To be able to develop algorithms allowing automatic item scoring, it is necessary to first verify the ability of the sensor to capture the requested movement of participants. The aim of the present feasibility study was to assess the ability of Kinect used during the completion of 14 of the 32 items of the MFM to capture the movements and postures of people with SMA with sufficient accuracy to provide appropriate item scoring.

METHODS

Study Design

This multicenter, prospective, noninterventional feasibility study was approved by the French ethics committee “Comité de protection des Personnes Sud est II” (#IRB 11236) and the Belgium ethics committee “Comité éthique du Centre Hospitalier Régional la Citadelle de Liège” (#ID RCB: 2014-A01 263-44).

Participants and Study Setting

Participants included in the study were enrolled between September 2015 and September 2017 in the Pediatric Neuro-Muscular Diseases reference center in Lyon (France), I-Motion Institute (Paris, France) and Neuro-Muscular Diseases reference center in Liege (Belgium). The inclusion criteria were people with genetically confirmed SMA type 2 or 3, and those between 2 years of age and older and 30 years of age and younger. Participants could be part of the SMA natural history study (NatHis-SMA, NCT02391831).²⁰

All therapists involved in the study had been previously trained and certified for MFM completion.

Motor Function Measure

Motor Function Measure consists of 32 items that evaluate 3 functional domains: D1, standing and transfers; D2, axial and

proximal motor function; and D3, distal motor function. For each item, the scoring system uses a 4-point Likert scale based on the participants' increasing ability to perform each task: 0 = cannot initiate the exercise or maintain the starting position; 1 = performs the task partially; 2 = performs the movement incompletely or completely but imperfectly, and 3 = performs the task fully and “normally.”

The proportion of the maximal score in each domain (D1, D2, and D3) is calculated, as is the proportion of the maximal score.⁸

Kinect

The Kinect V2 sensor (Microsoft, Redmond, Washington) was used. It is a markerless infrared-based motion capture and analysis system that tracks a digital skeleton composed of 25 points of the human body at a frame rate up to 30 frames per second. No marker placed on the person's body and no calibration of measurements is required for recording movements.

Development of Motion Display Software KiMe2

The KiMe2 software was developed by the G-SCOP laboratory (Grenoble, France) to display movement captured by the Kinect. This records the positions of the joints in 3 dimensions (3D) and records the persons' movements over time. It includes modules to facilitate the initial positioning of the person with respect to the camera's field of capture. The 3D reconstruction module of the digital skeleton enables the digital visualization of the person in both real time and retrospectively. Kinematic curves and digital skeleton 3D reconstruction are shown in Figure 1; see Supplemental Digital Content Video 1, available at: <http://links.lww.com/PPT/A414>.

Because of technical limitations, not all 32 items are suitable for the recording of the data using a Kinect sensor during completion of MFM. The KiMe2 software was developed to record data from 14 items of the MFM, items 9, 10, 11, 12, 13, 14, 15, 16, 24, 25, 26, 27, 31, and 32 (see Supplemental Digital Content 1, available at: <http://links.lww.com/PPT/A415>).

Conduct of the Study

Motor Function Measure was completed according to the MFM user's manual (see <http://www.mfm-nmd.org>). Participants were positioned at a distance of 1.5 to 2.5 m in front of the Kinect, facing and centered in the field of capture. For participants not involved in the NatHis-SMA study, the Kinect was at the height of his or her pelvis; for those involved in the NatHis-SMA study, the height of the Kinect was 1.50 m from the ground because of the ACTIVE-seated test that was part of the protocol.^{21,22}

During the completion of the 14 items suitable for recording by the Kinect, therapists recorded participants' movements with the Kinect by triggering and stopping the recording using a press button in the KiMe2 software. At the beginning of the capture, the screen was checked to verify that the system was working correctly. The therapist and/or the caregiver(s) accompanying the participant could be present in the Kinect field of capture without altering the capture of participant movements.

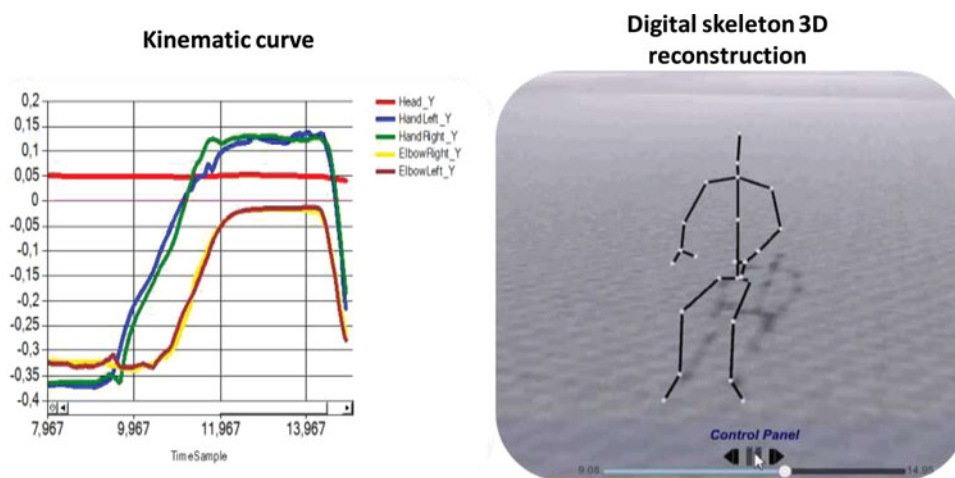


Fig. 1. Kinematic curve (left) and digital skeleton 3D reconstruction (right) display by KiMe2, example of item 15. Seated on a chair or a wheelchair, forearms on a table, the participant should place both hands on top of his or her head at the same time while the head and the trunk remain in the midline position. Kinematic curves shown represent the following movements of interest joints for item 15 according to time in seconds: head (in red), left hand (blue), right hand (green), left elbow (brown), and right elbow (yellow).

Data Collected

The day of MFM completion, participant demographic characteristics (gender, age), disease type (SMA type 2 or 3), walking ability (walking participants were those able to walk a 10-m distance indoors without assistance), and each score of the 32 MFM items given by the participant's therapist in real-time during the MFM completion (Score-T) were collected.

Based only on analyses of digital data presented by the KiMe2 software in the form of a 3D skeleton reconstruction and kinetic and kinematic curves (Figure 1; see Supplemental Digital Content Video 1, available at: <http://links.lww.com/PPT/A414>), recordings of completed items by the Kinect were further scored by a physiotherapist assisted by an engineer, masked to the participant's therapist score, giving a Score-D. Two MFM per participant could be collected provided there was at least 6-month interval between the 2 MFM.

Statistical Analysis

Quantitative variables were described as median, interquartile range. Categorical variables were described as frequencies or percentages.

The strength of agreement between items scores provided by the participant's therapist (Score-T) and from digital data (Score-D) was assessed by the proportion of agreement and disagreement for each item.

RESULTS

Twenty participants aged from 4 to 29 years were included, 10 of whom also participated in the Nathis-SMA study. Ten participants had SMA type 2 and 10 had SMA type 3. Thirteen, including 3 with SMA type 3, could not walk (Table 1).

MFM Completion and Item Recording

Sixteen participants completed only 1 MFM; 2 participants with SMA type 2 and 2 participants who were not walking and

TABLE 1

Participant Characteristics at Baseline

Age, y: median (IQR), y	10.7 (9–16.3)
Gender: Male/female, n	9/11
SMA type: 2/3, n	10/10
Walking status: walking/not walking, n	7/13
MFM scores: median (IQR), %	
MFM D1	5.9 (2.6–40.4)
MFM D2	91.7 (55.6–94.4)
MFM D3	93.4 (72.6–100)
MFM total score	58.3 (40.6–74.5)

Abbreviations: IQR, interquartile range; MFM, Motor Function Measure; SMA, Spinal muscular atrophy.

with SMA type 3 completed 2 MFM 6 months apart. For 4 MFM completions, participants completed items with a sitting starting position (items 14, 15, 16, and 24) in their electric wheelchair, instead of a chair of standardized height, as authorized by the MFM user's manual.

In 184 items, the starting position could not be achieved by the participants (score 0 for these items) preventing the completion of the items and their recording. For 10 items, items were not recorded because the participant's therapist forgot to start recording or there was a technical problem; 142 item recordings were therefore obtained and analyzed (Figure 2).

Agreement and Disagreement Between Scores From Therapist (Score-T) and Scores Based on Digital Data (Score-D)

Table 2 lists the distributions of agreement and disagreement among the 4 levels of MFM item scoring (0, 1, 2, and 3). Among the 142 items recording included in the analysis, there were 23 with a significant deformation of the skeleton (Table 2; see Supplemental Digital Content 2, available at: <http://links.lww.com/PPT/A416>), preventing item scoring based on digital data (Score-D). Such significant deformation of the skeleton

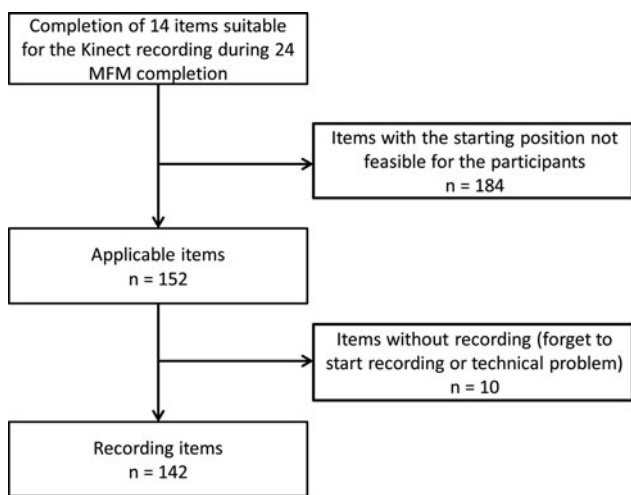


Fig. 2. Flowchart of the recorded items in the study. MFM indicates Motor Function Measure.

often occurred when the participant was leaning over or by capturing interference between the ground and extremities. When a Score-D was available, there were 29 disagreements; there was a difference of 1 point between Score-T and Score-D in all disagreements (Table 2).

There was agreement between Score-T and Score-D for 90 of 142 items (63.4%; Table 2). According to individual items, with the exception of item 13 “Maintain the seated position,” better agreements were in SMA type 3 than in type 2; overall, agreement was in 31.7% of recordings for SMA type 2 and 76.2% for SMA type 3 (Table 3).

For items 14 “raising the head” and 25 “standing straight,” disagreement (73.7% and 71.4%, respectively) was more

TABLE 2

Percentages of Agreement and Disagreement Between Scores From Therapists (Score-T) and Scores Based on Digital Data Analysis (Score-D)

	Agreements			Disagreements		
	Score-T/ Score-D ^a	n	%	Score-T/ Score-D ^a	n	%
n = 142	0/0	2	1.4	...	...	...
	1/1	17	12.0	...	...	...
	2/2	18	12.7	...	...	...
	3/3	53	37.3	...	...	...
	...	...	...	1/0	3	2.1
	...	...	...	2/1	2	1.4
	...	...	...	2/3	9	6.3
	...	...	...	3/2	15	10.6
	...	...	...	0/NK ^b	1	0.7
	...	...	...	1/NK ^b	4	2.8
	...	...	...	2/NK ^b	8	5.6
	...	...	...	3/NK ^b	10	7.0

Abbreviation: NK, not known.

^aThe scoring system uses a 4-point Likert scale (0-3) for each item, from score 0 when participant cannot initiate the task to score 3 when participant performs the task fully with a controlled movement.

^bA Score-D could not be determined on the basis of digital data because of a significant deformation of the skeleton during the course of the item completion (see Supplemental Digital Content 2, available at: <http://links.lww.com/PPT/A416>).

frequent than agreement. For these items, a lack of 3-axis misalignment capture that should be treated as a compensatory movement in the MFM scoring procedure led to a Score-D of 3 instead of 2.

DISCUSSION

This study had a medium level of agreement between scores given by the participant’s therapist in real time during the MFM completion and scores based on recorded digital data given by a therapist, assisted by an engineer for the 14 items tested. However, a higher level of agreement was found for participants with SMA type 3 than for those with SMA type 2.

The use of the Kinect was well received by therapists but some reported difficulties in obtaining the initial capture of the joints of weakest participants in their wheelchair during completion. As previously reported by Obdržálek et al,²³ the wheelchair often interferes with the capture of the skeleton by confusing the participants’ body envelope. In addition, although the Kinect has shown good performance in the capture of motor function or body joints in comparison with marker-based motion capture systems,²⁴⁻²⁶ some limitations have been identified to capture lower range movements.²⁷⁻²⁹ This could explain the better results achieved in participants with SMA type 3 than in those with SMA type 2 who experience more impairments and activity limitations.

The Kinect has been used mainly for rehabilitation programs,^{16,29,30} and it has more recently been used to assess motor function.^{17,18,22,27,31} Based on the results here, despite some good to excellent agreement between Score-T and Score-D for some items, such as items 11, 12, 24, 26, 27, or 32, the lower agreement found for other items prevents us from considering replacing therapist scoring by a fully automatic scoring based on Kinect capture. However, the Kinect coupled to the KiMe2 software allowed for capture and display of numerous compensatory movements. These results are thus encouraging to consider using the Kinect as a scoring aid, highlighting potential compensations. With feedback of the participant’s movements recorded by the system, the therapists could check some movements and analyze them in real time.

With the recent technological advancement, a new generation of sensors has been developed that provides more accurate kinematic measurements. For example, the Azure Kinect has greater accuracy in the anterior-posterior direction than the Kinect V2 with higher resolution³² and could give better results in the measurement of people with SMA.

Study Limitations

The small sample size is a study limitation, particularly because of the high clinical variability among people with SMA. Moreover, the participants were included from 2 different contexts; for half the MFM completion was the day of a routine clinical follow-up, while the other half were included in the SMA natural history study and for whom the MFM was completed the same day as many other tests.²⁰

TABLE 3

Agreement Between Score-T and Score-D

MFM Domain	MFM Item	SMA 2			SMA 3		
		Number of Recordings	Number of Identical Scoring	Percentage of Agreement	Number of Recordings	Number of Identical Scoring	Percentage of Agreement
D2	9	7	2	28.6	10	9	90.0
D2	10	7	2	28.6	12	9	75.0
D1	11	NA ^a	...	...	5	5	100
D1	12	NA ^a	...	...	5	5	100
D2	13	5	3	60.0	10	5	50.0
D2	14	10	2	20.0	9	3	33.3
D2	15	6	2	33.3	8	8	100
D2	16	6	2	33.3	11	10	90.9
D1	24	NA ^a	...	...	7	6	85.7
D1	25	NA ^a	...	...	7	2	28.5
D1	26	NA ^a	...	...	6	6	100
D1	27	NA ^a	...	...	5	4	80.0
D1	31	NA ^a	...	...	3	2	66.7
D1	32	NA ^a	...	-	3	3	100
Total		41	13	31.7	101	77	76.2

Abbreviations: MFM, Motor Function Measure; NA, not applicable; SMA, Spinal muscular atrophy.

^aItem for which the starting position could not be achieved by the participants.

CONCLUSION

The results of the present study prevent us from considering the use of Kinect capture to propose an automated scoring for MFM in people with SMA, particularly in the weakest participants, but may be of interest as a scoring aid, highlighting potential compensations. These preliminary results could be improved in the future with more accurate capture tools.

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REFERENCES

- Verhaart IEC, Robertson A, Leary R, et al. A multi-source approach to determine SMA incidence and research ready population. *J Neurol*. 2017;264(7):1465-1473. doi:10.1007/s00415-017-8549-1.
- Munsat TL, Davies KE. International SMA consortium meeting (26-28 June 1992, Bonn, Germany). *Neuromuscul Disord*. 1992;2(5):423-428. doi:10.1016/S0960-8966(06)80015-5.
- Lunn MR, Wang CH. Spinal muscular atrophy. *Lancet*. 2008;371(9630):2120-2133. doi:10.1016/S0140-6736(08)60921-6.
- Finkel R, Bertini E, Muntoni F, Mercuri E; ENMC SMA Workshop Study Group. 209th ENMC International Workshop: outcome measures and clinical trial readiness in spinal muscular atrophy 7-9 November 2014, Heemskerk, The Netherlands. *Neuromuscul Disord*. 2015;25(7):593-602. doi:10.1016/j.nmd.2015.04.009.
- Messina S, Sframeli M. New treatments in spinal muscular atrophy: positive results and new challenges. *J Clin Med*. 2020;9(7):2222. doi:10.3390/jcm9072222.
- Kirschner J, Butoianu N, Goemans N, et al. European ad-hoc consensus statement on gene replacement therapy for spinal muscular atrophy. *Eur J Paediatr Neurol*. 2020;28:38-43. doi:10.1016/j.ejpn.2020.07.001.
- Iftikhar M, Frey J, Shohan MdJ, Malek S, Mousa SA. Current and emerging therapies for Duchenne muscular dystrophy and spinal muscular atrophy. *Pharmacol Ther*. 2021;220:107719. doi:10.1016/j.pharmthera.2020.107719.
- Bérard C, Payan C, Hodgkinson I, Fermanian J; MFM Collaborative Study Group. A motor function measure for neuromuscular diseases. Construction and validation study. *Neuromuscul Disord*. 2005;15(7):463-470.
- de Lattre C, Payan C, Vuillerot C, et al. Motor function measure: validation of a short form for young children with neuromuscular diseases. *Arch Phys Med Rehabil*. 2013;94(11):2218-2226. doi:10.1016/j.apmr.2013.04.001.
- Jacqmin P, Gieschke R, Delor I, et al. Mathematical disease progression modeling in type 2/3 spinal muscular atrophy. *Muscle Nerve*. 2018;58(4):528-535. doi:10.1002/mus.26178.
- Vuillerot C, Payan C, Iwaz J, Ecochard R, Bérard C; MFM Spinal Muscular Atrophy Study Group. Responsiveness of the motor function measure in patients with spinal muscular atrophy. *Arch Phys Med Rehabil*. 2013;94(8):1555-1561.
- Servais L. Video games to measure outcome for children with neuromuscular disorders. *Dev Med Child Neurol*. 2019;62(3):266. doi:10.1111/dmcn.14231.
- Rocha AP, Choupina HMP, Vilas-Boas M do C, Fernandes JM, Cunha JPS. System for automatic gait analysis based on a single RGB-D camera. *PLoS One*. 2018;13(8):e0201728.
- Bonnechère B, Sholukha V, Omelina L, Van Sint Jan S, Jansen B. 3D analysis of upper limbs motion during rehabilitation exercises using the Kinect™ sensor: development, laboratory validation and clinical application. *Sensors*. 2018;18(7):2216.
- Lopez N, Perez E, Tello E, Rodrigo A, Valentinuzzi ME. Statistical validation for clinical measures: repeatability and agreement of Kinect™-based software. *BioMed Res Int*. 2018;2018:6710595. doi:10.1155/2018/6710595.
- Clark RA, Mentiplay BF, Hough E, Pua YH. 3-dimensional cameras and skeleton pose tracking for physical function assessment: a review of uses, validity, current developments and Kinect alternatives. *Gait Posture*. 2019;68:193-200. doi:10.1016/j.gaitpost.2018.11.029.
- Cai L, Ma Y, Xiong S, Zhang Y. Validity and reliability of upper limb functional assessment using the Microsoft Kinect V2 sensor. *Appl Bionics Biomech*. 2019;2019:7175240. doi:10.1155/2019/7175240.
- Scano A, Chiavenna A, Malosio M, Molinari Tosatti L, Molteni F. Kinect V2 implementation and testing of the reaching performance scale for motor evaluation of patients with neurological impairment. *Med Eng Phys*. 2018;56:54-58. doi:10.1016/j.medengphy.2018.04.005.

19. Mousavi Hondori H, Khademi M. A review on technical and clinical impact of Microsoft Kinect on physical therapy and rehabilitation. *J Med Eng.* 2014;2014:846514. doi:10.1155/2014/846514.
20. Chabanon A, Seferian AM, Daron A, et al. Prospective and longitudinal natural history study of patients with type 2 and 3 spinal muscular atrophy: baseline data NatHis-SMA study. *PLoS One.* 2018; 13(7):e0201004. doi:10.1371/journal.pone.0201004.
21. Lowes LP, Alfano LN, Yetter BA, et al. Proof of concept of the ability of the Kinect to quantify upper extremity function in dystrophinopathy. *PLoS Curr.* 2013;5. doi:10.1371/currents.md.9ab5d872bbb944c6035c9f9bfd314ee2.
22. Lowes LP, Alfano LN, Crawfis R, et al. Reliability and validity of active-seated: an outcome in dystrophinopathy. *Muscle Nerve.* 2015;52(3):356-362. doi:10.1002/mus.24557.
23. Obdržálek S, Kurillo G, Ofli F, et al. Accuracy and robustness of Kinect pose estimation in the context of coaching of elderly population. *Annu Int Conf IEEE Eng Med Biol Soc.* 2012;2012:1188-1193. doi:10.1109/EMBC.2012.6346149.
24. Otte K, Kayser B, Mansow-Model S, et al. Accuracy and reliability of the Kinect Version 2 for clinical measurement of motor function. *PLoS One.* 2016;11(11):e0166532. doi:10.1371/journal.pone.0166532.
25. Ma M, Proffitt R, Skubic M. Validation of a Kinect V2 based rehabilitation game. *PLoS One.* 2018;13(8):e0202338. doi:10.1371/journal.pone.0202338.
26. Hu G, Wang W, Chen B, et al. Concurrent validity of evaluating knee kinematics using Kinect system during rehabilitation exercise. *Med Nov Technol Devices.* 2021;11:100068. doi:10.1016/j.medntd.2021.100068.
27. Galna B, Barry G, Jackson D, Mhiripiri D, Olivier P, Rochester L. Accuracy of the Microsoft Kinect sensor for measuring movement in people with Parkinson's disease. *Gait Posture.* 2014;39(4):1062-1068. doi:10.1016/j.gaitpost.2014.01.008.
28. Mortazavi F, Nadian-Ghomsheh A. Stability of Kinect for range of motion analysis in static stretching exercises. *PLoS One.* 2018;13(7):e0200992. doi:10.1371/journal.pone.0200992.
29. Webster D, Celik O. Systematic review of Kinect applications in elderly care and stroke rehabilitation. *J Neuroengineering Rehabil.* 2014;11:108. doi:10.1186/1743-0003-11-108.
30. Da Gama A, Fallavollita P, Teichrieb V, Navab N. Motor rehabilitation using Kinect: a systematic review. *Games Health J.* 2015;4(2):123-135. doi:10.1089/g4h.2014.0047.
31. Blaschek A, Hesse N, Warken B, et al. Quantitative motion measurements based on markerless 3D full-body tracking in children with SMA highly correlate with standardized motor assessments. *J Neuromuscul Dis.* 2022;9(1):121-128. doi:10.3233/JND-200619.
32. Yeung LF, Yang Z, Cheng KCC, Du D, Tong RKY. Effects of camera viewing angles on tracking kinematic gait patterns using Azure Kinect, Kinect v2 and Orbbec Astra Pro v2. *Gait Posture.* 2021;87:19-26. doi:10.1016/j.gaitpost.2021.04.005.