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Validity of Markerless Motion Capture System and Its Correlation with Physical Characteristics for Hip Range of Motion Measurement: A Pilot Study

Se-Young Bak,[1*] Junghoon Ahn,[2] Hongtaek Choi,[1]
Seunghee Lee,[1] Wootaek Lim,[3,4] and Hyeong-Dong Kim[1**]

[1]Department of Health Science, Graduate School, Korea University,
145, Anam-ro, Seongbuk-gu, Seoul, Republic of Korea
[2]Department of Sports Rehabilitation, Cheongju University,
298, Daeseong-ro, Cheongwon-gu, Cheongju-si, Chungcheongbuk-do, Republic of Korea
[3]Department of Physical Therapy, Woosong University, 171, Dongdaejeon-ro, Dong-gu, Daejeon, Republic of Korea
[4]Department of Digital Bio-Health Convergence, Woosong University,
171, Dongdaejeon-ro, Dong-gu, Daejeon, Republic of Korea

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For existing measurements of the hip range of motion (ROM), marker-based motion capture systems (MBSs) are utilized as a gold standard, even though they have disadvantages such as high cost and inconvenience due to the need for marker attachment. To address these limitations, a novel markerless motion capture system (MLS) is suggested. An MLS might be affected by environmental and physical factors; however, no existing research has been conducted on the relationship between the validity of MLSs and individual physical characteristics including height, leg length, knee width, and body mass index (*BMI*). The purpose of this study was to confirm the overall validity of MLSs in estimating hip joints and the correlation between the validity and physical characteristics. Hip angles were collected using an MBS and an MLS during single-joint motions. Intraclass correlation coefficient (*ICC*; 3,1) analysis demonstrated a high validity (0.870–0.996) of the MLS. Groups classified by height, leg length, and *BMI* showed clinical differences (thresholds: 2–5°) in root mean square error (*RMSE*). Height and leg length showed a negative correlation with the *RMSE* in a Spearman analysis. From the results of this study, we confirmed that the novel MLS is highly promising for measuring the hip ROM, although the validity of MLSs could be affected to some extent by physical characteristics.

1. Introduction

The range of motion (ROM) is a critical indicator for assessing functional ability across various fields, including physiotherapy, sports, medical science, and biomechanics.(1,2) In these areas, ROM measurement is recognized as a fundamental baseline indicator.(3) Specifically, the hip joint ROM plays a pivotal role in diagnosing conditions such as osteoarthritis, lower back

*Corresponding author: e-mail: seyoung123@korea.ac.kr
**Corresponding author: e-mail: hdkimx0286@korea.ac.kr
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pain, and chronic groin injury.[4,5] Additionally, the hip joint ROM is crucial as a kinematic factor that affects gait patterns and speed, both of which are vital components of rehabilitation strategies.[6,7] Therefore, the accurate measurement of the hip joint ROM is essential. For this purpose, a variety of methods, from conventional goniometers to high-tech marker-based camera systems such as Qualysis and Vicon, are commonly utilized.[8,9)

Goniometers are easy to use, inexpensive, and fairly accurate on static states. Hence, they are used generally in clinics or small hospitals. However, measurement standards could be different from user to user, and they could be inaccurate when estimating dynamic states.[9] Marker-based motion capture systems (MBSs), which have high accuracy, have been applied in various experiments and utilized in many laboratories. However, they have some disadvantages, including a high cost,[10] the necessity of a large space, such as a laboratory,[11] and the inconvenience of marker attachment. In addition, anatomical knowledge is demanded of the users who are attaching the markers.[12]

Given these considerations, markerless cameras have been actively researched. [13] A recently developed multiview markerless system has advantages, including cost and convenience. In the novel markerless motion capture system (MLS), image analysis technology based on markerless pose estimation is used to achieve motion tracking.[14] Markerless evaluation systems, which leverage human posture estimation algorithms, potentially offer greater user-friendliness and commercial viability than MBSs.[15] Previous studies have also highlighted the reliability and validity of such systems.[14,16]

Kanko *et al.*[17] emphasized further studies, including subject characteristics and environmental factors, since an MLS could be affected by several factors, such as age, health status, anatomical deformities, and lighting. Keller *et al.*[18] stated that the identification of anatomical features using an MLS including joint centers could even be perturbed by clothing on extremity segments. Furthermore, in rotational movements, even if the displacement is the same, the angle change due to the displacement could increase as the distance from the rotation axis decreases. That means that the MLS's validity could be varied by physical characteristics including extremity length. Hence, to establish a development strategy for the commercialization of the MLS, its sensitivity regarding subjects' physical characteristics, including height, leg length, and knee width, must be tested.

For the novel MLS, despite previous studies proving its reliability and validity to some extent,[14,16] no existing research has investigated the relationship between the validity of the MLS and individual physical characteristics. Since the MLS has been developed recently, its necessity to be researched was still demanded. Accordingly, this study aims to verify the novel MLS's validity of hip-joint ROM measurements, including its correlation with physical characteristics.

2. Methods

2.1 Participants

Eleven healthy adult volunteers (mean age: 23.82 ± 3.25 years) were recruited for this pilot and cross-sectional study. In line with the exclusion criteria detailed in a previous study,[14] individuals with a history of neurological, musculoskeletal, or cognitive disorders were excluded. The participants were fully briefed on the experiment protocols and objectives, and they voluntarily provided their consent. Height (171.00 ± 10.92 cm), weight (65.27 ± 17.14 kg), leg length (880.45 ± 74.31 mm), and knee width (93.35 ± 8.00 mm) were collected as physical characteristics. The measured values were averaged between the left and right sides. The body mass index (*BMI*) was calculated using Eq. (1). The Bioethics Review Committee of Korea University (KUIRB, no. 2022-0260-01) approved for this study.

$$BMI = weight\ (\mathrm{kg})/Height\ (\mathrm{m})^2 \tag{1}$$

2.2 Procedures

Six Vicon infrared cameras (MX-T10, Vicon Motion Capture System Ltd., Oxford, UK) and five RGB cameras (4D EYE, SYM healthcare, Seoul, Korea) were installed in the laboratory. Both systems simultaneously captured the motions of subjects. The experimental environment is shown in Fig. 1.

For each participant, 40 trajectories (4 motions × 5 repetitions × 2 sides) of hip single joint motions (Fig. 2) on the sagittal or coronal plane were collected. Single joint motions were defined as active motions from a standing anatomic posture to an end-range motion on the coronal or sagittal plane. These hip motions included flexion, extension, abduction, and adduction. To standardize the capturing environment, participants performed the motions within the designated site (60 × 60 cm^2), approximately 180 cm away from the cameras in front of them. Participants could take a 3–5 min rest between motions to avoid fatigue. Additionally, the examiner, a licensed physical therapist, monitored the participants' overall condition and movement execution throughout the experiment.

For data capture using the Vicon system, a plug-in-gait full body model template was employed, comprising 35 markers (each 14 mm in diameter) at a sampling rate of 100 Hz. The NEXUS software version 1.8.5 (Vicon Motion Capture System Ltd., Oxford, UK) was used for capturing and addressing gaps in the data to accurately represent landmark location information. Postprocessing was conducted using Visual 3D (C-Motion Inc., Germantown, USA). Among the markers, four specific ones [left anterior superior iliac spine (ASIS), right ASIS, left knee, right knee] were selected for analysis. Hip angles were calculated in the Vicon system using the vector from the hip joint center (HJC) to the knee joint center (KJC), which served as a moving line, with a reference to one of the virtual three-dimensional axes formed by the absolute axes in the laboratory. The formulas for determining the HJCs whose origin was the midpoint of ASIS markers are as follows.

$$\begin{aligned} &Right\ HJC(x,y,z) = 0.36 \times ASIS\_Distance, -0.19 \times ASIS\_Distance, -0.3 \times ASIS\_Distance \\ &Left\ HJC(x,y,z) = -0.36 \times ASIS\_Distance, -0.19 \times ASIS\_Distance, -0.3 \times ASIS\_Distance \end{aligned} \tag{2}$$

In the MLS (4D EYE), the moving line was a vector from the HJC to the KJC, and the criterion was a line connecting the middle point of the shoulders to the middle point of the HJC. The MLS was set at a frequency of 12 Hz. All landmarks (27 landmarks) and the angle result of

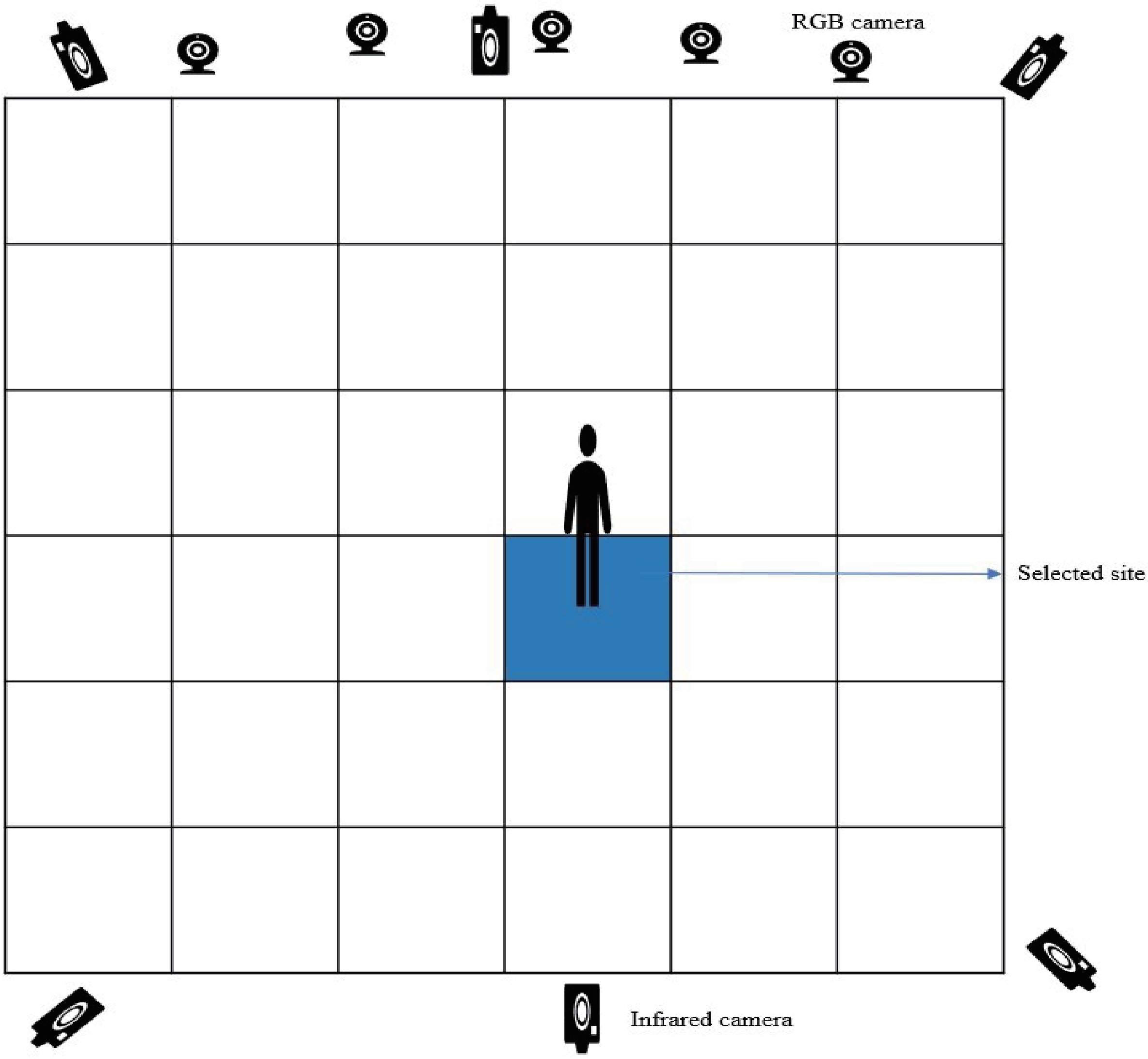


Fig. 1. (Color online) Camera placement for motion capture. Five RGB cameras and three infrared cameras were positioned in front of the capture area.

each joint were recognized and automatically calculated by analysis programs based on an open source computer vision library and OpenPose,[14] which is a representative deep learning-based model for estimating posture.[16] The model takes a bottom-up approach, first recognizing the human segment in the image and then finding and grouping the main parts of each individual on the basis of the detection results.[16] Hence, it did not require any postprocessing program. The angle of the MLS was defined as between two lines formed in a plane that included the criterion and moving lines. The ROM values of the MBS and MLS were utilized to confirm the validity of these systems. The ROM value was defined as the gap between the maximum and minimum values on each trajectory. The maximum and minimum values were extracted from the raw data of each trajectory.

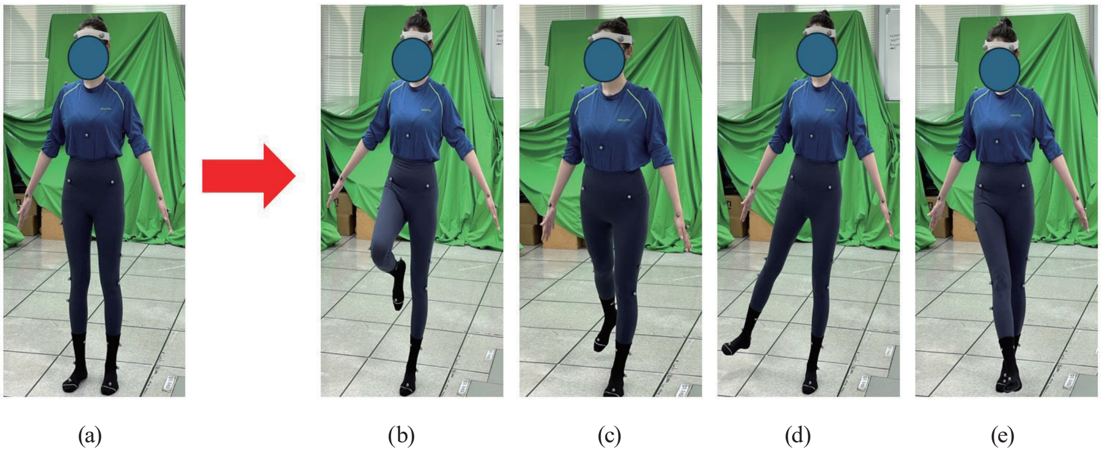


Fig. 2. (Color online) Sample images of motions in the experiment. (a) Initial posture; (b), end posture of hip flexion; (c), end posture of hip extension; (d), end posture of hip abduction; (e), end posture of hip adduction.

2.3 Statistical analysis

Intraclass correlation coefficients (*ICC*s), 95% confidence intervals (*CI*s), and the root mean square error (*RMSE*) were used to confirm the validity of the hip joint ROM of the MLS by comparison with the MBS. The *ICC* model was two-way mixed (3,1) and the type was absolute agreement. To obtain each participant's overall hip motion validity, all ROM values of each trajectory were used as variables. A Spearman analysis, which is a non-parametric correlation analysis, was applied to confirm the correlation results among physical characteristics and the *RMSE*. The purpose of this analysis was to identify possible similarities among participant assignments categorized by characteristics that could affect the results. To set averages as criteria for subgroup classification by physical characteristics, the estimated values of each characteristic were tested for normality by the Shapiro–Wilk test. A Bland–Altman plot analysis was utilized to confirm the agreement between the two motion capture systems for each subgroup. SPSS version 25 (SPSS Inc., Chicago, USA) and Microsoft Excel (Microsoft Inc., Redmond, USA) were utilized for statistical analysis.

3. Results

Table 1 shows the validity of hip ROM, on the basis of the physical characteristics of the participants. The *ICC* values ranged from 0.870 to 0.996, with all *p*-values being below 0.001. The *RMSE* values ranged from 1.634 to 10.181°, with the lowest *RMSE* corresponding to the highest *ICC* value (subject 3) and the highest *RMSE* corresponding to the lowest *ICC* value (subject 2).

The Shapiro–Wilk test was applied to set criterion values as the averages of sample groups using the estimated values of physical characteristics (height, weight, leg length, and knee width). In the test, the significance level was generally set as 0.05, and if the significant values were less than the significance level, the normality requirement satisfaction of the sample data

Table 1
Validity of hip ROM and physical characteristics of subjects.

Subject	Physical characteristics (Rank)						Hip motion validity		
	Gender (male/female)	Height (cm)	Weight (kg)	*BMI*	Leg length (mm)	Knee width (mm)	*ICC* (3,1)	95% *CI*	*RMSE* (°)
1	female	158(10)	50(9)	20.029(7)	815(8)	90(6)	**0.924*****	0.763–0.968	9.457
2	female	161(9)	55(8)	21.218(6)	790(10)	94(5)	**0.870*****	0.765–0.929	10.181
3	male	183(2)	65(5)	19.409(9)	1000(1)	97(4)	**0.996*****	0.992–0.998	1.634
4	male	181(3)	94(2)	28.693(1)	900(5)	105(1)	**0.966*****	0.936–0.982	5.711
5	male	181(3)	73(3)	22.283(4)	930(4)	97.5(3)	**0.950*****	0.895–0.975	5.369
6	male	185(1)	98(1)	28.684(2)	950(2)	M/E	**0.963*****	0.923–0.981	4.341
7	female	170(7)	57(6)	19.723(8)	910(6)	89(8)	**0.966*****	0.937–0.982	7.847
8	female	164(8)	70(4)	26.026(3)	810(9)	105(1)	**0.936*****	0.882–0.965	4.550
9	female	171(6)	56(7)	19.151(10)	870(7)	90(6)	**0.969*****	0.752–0.990	5.507
10	female	174(5)	50(9)	16.515(11)	940(3)	80(10)	**0.987*****	0.967–0.994	4.136
11	female	153(11)	50(9)	21.359(5)	785(11)	86(9)	**0.918*****	0.684–0.968	6.593

Rank is given in descending order. Subjects who had the same estimated values are listed as the same rank.
*** $p < 0.001$. *ICC*: intraclass correlation coefficient. M/E: misestimation. *BMI*: body mass index. *RMSE*: root mean square error.

could be rejected. Only the weight data showed $p > 0.05$ in the Shapiro–Wilk test. Hence, the weight data were excluded from the Bland–Altman plot analysis. The average values of samples satisfying the normality test were used as criteria for categorizing subgroups by physical characteristics. The values were 171 cm (height), 880.45 mm (leg length), and 93.35 mm (knee width).

Table 2 presents the Spearman correlation results of the physical characteristics and *RMSE*. In the correlation analysis, one (misestimation) of the estimated knee width values was excluded. Hence, the number of samples compared with knee width was 10, and the other variables had a sample size of 11. Height and leg length showed negative correlations (−0.720, $p = 0.013$ and −0.727, $p = 0.011$) with *RMSE*. Height and leg length had a positive correlation (0.893; $p < 0.001$) with each other. Knee width showed positive correlations with weight (0.852, $p < 0.001$) and *BMI* (0.701, $p = 0.024$).

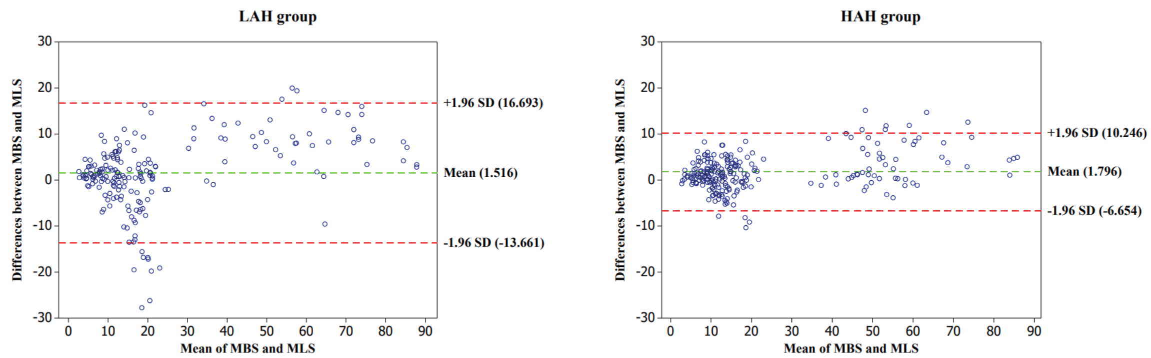
As a result of classification by physical characteristics, the lower than average height (LAH) group included five persons, and the higher than average height (HAH) group included six persons. The lower than average leg length (LAL) group included five persons, and the higher than average leg length (HAL) group included six persons. Because one of the knee width data was excluded owing to misestimation, the lower than average knee width (LAK) group and the higher than average knee width (HAK) group each included five persons. According to a Korean Society for the Study of Obesity standard,[19] *BMI* could be classified as follows: underweight <18.5 kg/m^2; normal 18.5 kg/m^2; overweight ≥23 kg/m^2; obese (1st stage) ≥25 kg/m^2; obese (2nd stage) ≥30 kg/m^2; severely obese ≥35 kg/m^2. In this study, no one had a *BMI* of ≥30 kg/m^2; hence, for convenience, the group presenting a *BMI* of ≥25 kg/m^2 was called the obese group. Depending on the standard, the samples were classified into three groups: underweight group (n = 1), normal group (n = 7), and obese group (n = 3).

Figure 3 shows the Bland–Altman classifications with physical characteristics. The mean values of all groups are 0.284–3.048. The HAH group [95% limits of agreement (*LOA*) ± 8.450°]

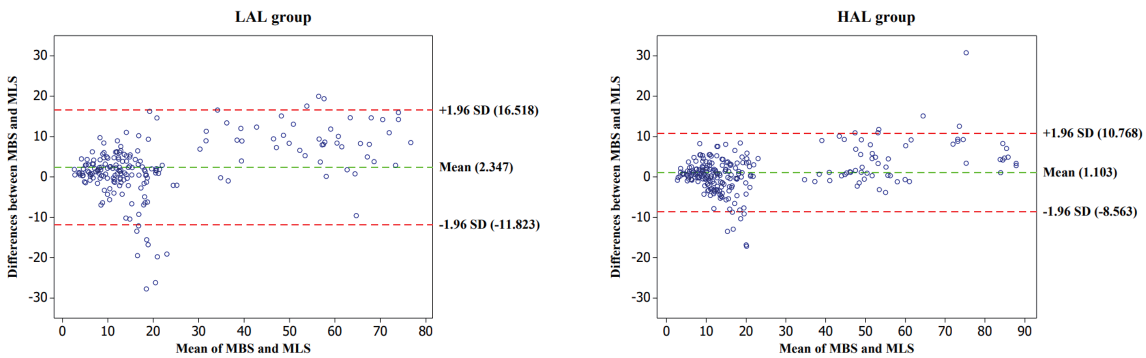
Table 2
Spearman correlation results among the physical characteristics including *RMSE*.

		Height	Weight	*BMI*	Leg length	Leg length/ Height	Knee width
Weight	rho	0.740**					
	p-value	0.009					
BMI	rho	0.141	0.670**				
	p-value	0.679	0.024				
Leg length	rho	0.893***	0.459	−0.182			
	p-value	0.000	0.156	0.593			
Leg length/ Height	rho	0.328	−0.183	−0.555	0.700**		
	p-value	0.325	0.589	0.077	0.016		
Knee width	rho	0.394	0.852**	0.701**	0.018	−0.470	
	p-value	0.259	0.002	0.024	0.960	0.171	
RMSE	rho	−0.720**	−0.376	0.109	−0.727**	−0.427	−0.183
	p-value	0.013	0.254	0.750	0.011	0.190	0.613

***p* < 0.05, ****p* <0.001, *BMI*: body mass index, and *RMSE*: root mean square error.

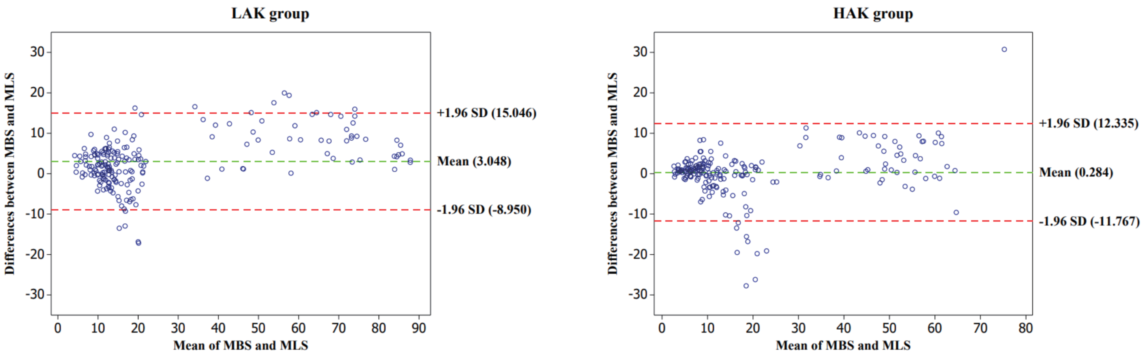


(a)

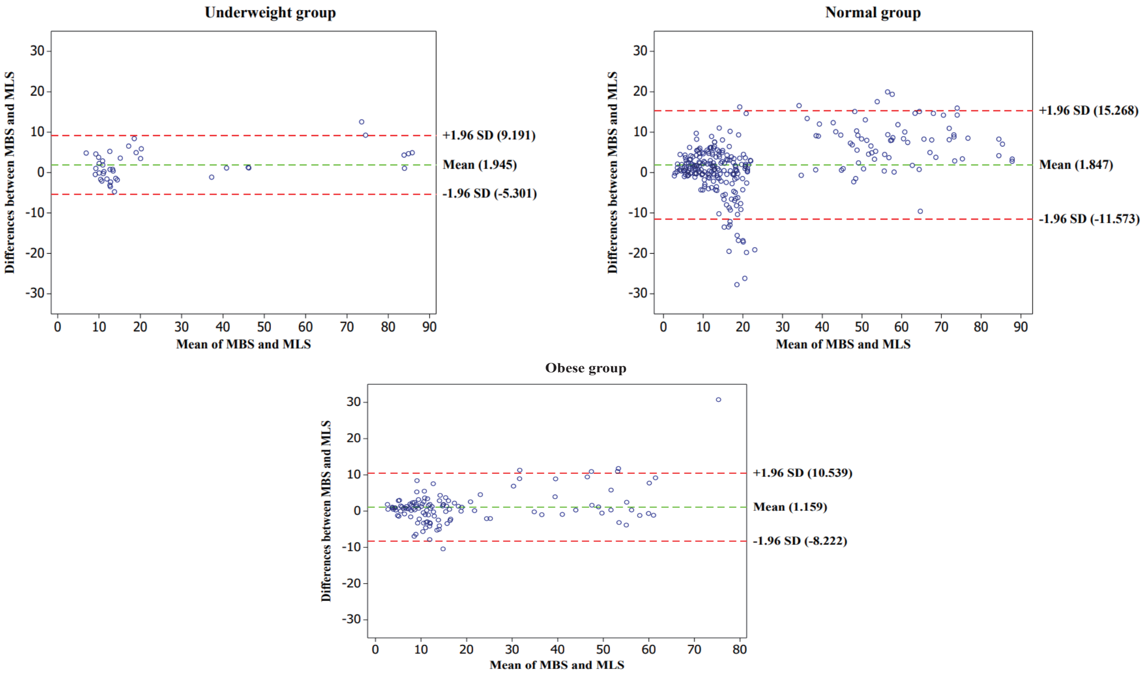


(b)

Fig. 3. (Color online) Bland–Altman plots of MBS and MLS, categorized by physical characteristics. (a) Subgroups classified by height; (b), subgroups classified by leg length; (c), subgroups classified by knee width; (d), subgroups classified by *BMI*. *SD*, standard deviation; unit, degree (°); LAH, lower than average height; HAH, higher than average height; LAL, lower than average leg length; HAL, higher than average leg length; LAK, lower than average knee width; HAK, higher than average knee width; MBS, marker-based motion capture system; MLS, markerless motion capture system



(c)



(d)

Fig. 3. (Continued) (Color online) Bland–Altman plots of MBS and MLS, categorized by physical characteristics. (a) Subgroups classified by height; (b), subgroups classified by leg length; (c), subgroups classified by knee width; (d), subgroups classified by *BMI*. *SD*, standard deviation; unit, degree (°); LAH, lower than average height; HAH, higher than average height; LAL, lower than average leg length; HAL, higher than average leg length; LAK, lower than average knee width; HAK, higher than average knee width; MBS, marker-based motion capture system; MLS, markerless motion capture system

showed a higher accuracy than the LAH group (95% *LOA* ± 15.177°). The HAL group (95% *LOA* ± 9.666°) also showed a higher accuracy than the LAL group (95% *LOA* ± 14.170°). No clear difference in accuracy was observed between the HAK group (95% *LOA* ± 12.051°) and the LAK group (95% *LOA* ± 11.998°). In terms of *BMI*, the accuracy was high in the order of the underweight group (95% *LOA* ± 7.246°), obese group (95% *LOA* ± 9.380°), and normal group (95% *LOA* ± 13.421°). *RMSE* values of subgroups classified on the basis of physical characteristics are shown in Table 3. Furthermore, there was no siginificant difference in *RMSE* between subgroups classified by gender (Mann–Whitney test, $p = 0.164$).

Table 3
Spearman correlation results among the physical characteristics including *RMSE*.

Subgroup	*Mean* ± *SD*
HAH group (*n* = 6)	4.450° ±1.523°
LAH group (*n* = 5)	7.606° ±2.266°
HAL group (*n* = 6)	4.740° ±1.887°
LAL group (*n* = 5)	7.258° ±2.461°
HAK group (*n* = 5)	5.489° ±3.075°
LAK group (*n* = 5)	6.588° ±1.990°
Underweight group (*n* = 1)	4.136°
Normal group (*n* = 7)	6.570° ±2.851°
Obese group (*n* = 3)	4.868° ±0.738°

RMSE, root mean square error; *SD*, standard deviation

4. Discussion

The aim of our study was to confirm the validity of the hip joint ROM, including its correlation with physical characteristics, of the novel MLS. The subgroups identified in the Bland–Altman plot analysis demonstrated different means and 95% *LOA* widths. *RMSE* values of individuals displayed negative Spearman correlations with height (−0.720) and leg length (−0.727). Furthermore, the *RMSE* values of subgroups classified by height, leg length, and *BMI* showed clinical differences (thresholds: 2–5°). The results showed validity differences to some extent among subgroups; however, the novel markerless system showed high validity [*ICC* (3,1) = 0.870–0.996]. Hence, in this study, the novel MLS was verified to be highly acceptable.

The *ICC* was used to confirm the overall validity of the MLS. The *ICC* could be categorized using the results of Koo and Li;[20] the classification criteria were as follows: almost perfect, 0.81–1.0; substantial, 0.61–0.80; moderate, 0.41–0.60; fair, 0.21–0.40; slight, 0.00–0.20. In this experiment, all participants' *ICC* values were in the almost perfect range, again demonstrating the high validity [*ICC* (3,*k*) = 0.902 and 0.936; 95% *CI* = 0.606–0.976] shown in prior research,[14] which included the estimation of hip flexion during squat movement. Additionally, in another previous study[16] regarding hip rock (movements combining hip flexion, knee flexion, and trunk rotation), hip flexion [*ICC* (3,*k*) = 0.958–0.998 on the left side and *ICC* (3,*k*) = 0.973–0.997 on the right side] was observed. Furthermore, a Bland–Altman plot analysis was used to confirm the accuracy agreement among subgroups classified by physical characteristics. The results also showed different means and widths of 95% *LOA*s among subgroups. To an extent, the overall results were similar to those obtained by Musha *et al.*,[13] who investigated the agreement of the deep-learning-based MLS and MBS (hip mean, 1.1° ± 3.5°; *LOA*, -5.58–8.02°). The *RMSE* (5.884° ± 2.435°) values were similar to those of Van Hooren *et al.*,[21] who reported an average of 5–7° for running kinematics recorded with OpenPose compared with a marker-based approach. Horsak *et al.*[22] mentioned that 2–5° has been a desirable threshold in previous studies. The *RMSE* values of the HAH group (4.450°), HAL group (4.740°), underweight group (4.136°), and obese group (4.868°) were lower than the thresholds. The other subgroups showed values above the thresholds, but no gross gaps from the corresponding thresholds.

In groups classified by height and leg length, groups of higher than average characteristics had lower *RMSE* values and a higher accuracy than did groups of lower than average characteristics. This similarity could have occurred because the leg length showed a positive correlation with height (Spearman correlation coefficient value, 0.893; $p < 0.001$). This result might imply that the distances between landmarks could affect the validity of the novel MLS. The MLS formulated moving lines using virtual landmarks based on OpenPose via a bottom-up approach. Even if the displacement is the same, the change in angle caused by the displacement might increase as the distances from the rotation axis decreases (the distance between the HJC and the KJC being smaller). Knee width could be related to recognizing landmarks; however, no clinical difference or correlation with *RMSE* was shown. The results imply that the lines formed by two landmarks (one dimension) could have a larger effect on the MLS than the recognition of only one landmark (zero dimension). The height, leg length, and *BMI* showed clinically significant differences (thresholds: 2–5°) in terms of *RMSE*. These factors could be related to subject body sizes. Zago *et al.*[23] demonstrated, by controlling the distance from the camera, that a smaller subject aggravated the optical measurements. In our study (with fixed distances from cameras), relative differences among the subgroups regarding the imaged body (caused by physical characteristics) could indicate a situation similar to that described by Zago *et al.*[23] The underweight group showed a low *RMSE* value and a narrow *LOA* 95% limit; however, the group included only one subject who was tall and had a long leg. Leg length/height showed no correlation with *RMSE*, and this result might suggest that absolute body length or size could be more significant than body shape, including body proportion.

Overall, hip motion validity was high; however, some trajectories showed large differences in the Bland–Altman plot analysis. The predetermined landmarks of OpenPose were derived from a vast library of named learning images.[24] Cronin *et al.*[25] mentioned that the images of this library could be unfamiliar with reflecting the motions (long jump movement) of the study. Similarly, the instructed postures in our study are not generally applied for estimation in daily life or medical fields. Hence, the unfamiliar postures could have been difficult to estimate and track. An MLS consisting of five cameras based on OpenPose could have tracking errors; however, this could be upgraded by increasing the number of cameras.[26] Despite the possibility of a reduced validity, a high *ICC* validity could prove the MLS's acceptability as a measuring system of the hip ROM. Additionally, if deep learning through data accumulation is continuously performed, the novel MLS could become more accurate and consistent as it becomes familiar with the various physical characteristics and motions.

Our study has some limitations. First, the location data of landmarks (MLS) and markers (MBS) were not collected. If they existed, more specific and various comparisons could have been applied to obtain validity. Second, the sample size was not large enough for generalization. This study was a pilot study, and thus, a sufficient number of participants was not recruited. Hence, further study designed to assign an adequate number of subjects to each subgroup will be required. Third, a reliability test was not included. In this study, subjects actively performed their motions in a standing position. Various elements, such as balance, muscle strength, and momentary physical condition could affect the performance of the motion. Demonstrating consistency in the ROM values, even for the same repeated motion, was difficult. Hence, a reliability test was excluded in this study. The last physical characteristics could be related to gender; however, this study could not show the difference between genders due to the insufficient number of participants. In further study, research considering the genders could be designed.

5. Conclusions

Although conventional methods like goniometers and MBS have generally been employed to measure ROM, they had some disadvantages. To address the limitations, an MLS could be an alternative, and a novel multiview MLS has recently been developed. However, the validity of the novel MLS needed to be confirmed. Furthermore, it could be affected by various factors including the physical characteristics of the subjects. Hence, we confirmed the MLS validity and the correlation between this validity and the physical characteristics of the subjects through comparison with an MBS as the gold standard. From the results of this study, we confirmed that the novel MLS could be highly acceptable to measure the hip joint ROM in various fields despite the effects of physical characteristics on the novel MLS, since high *ICC* was presented in overall participants. However, development considering the influenceable factors could ultimately be needed for establishing more stable and accurate performance.

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