Journal of Biomechanics 164 (2024) 111975

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech

Conventional video recordings dependably quantify whole-body lifting strategy using the Stoop-Squat-Index: A methods comparison against motion capture and a reliability study

Christian Bangerter [a,b,*], Oliver Faude [b], Patric Eichelberger [a], Annina Schwarzentrub [a], Milène Girardin [a], Aglaja Busch [a], Carol-Claudius Hasler [c,d], Stefan Schmid [a,d]

[a] Spinal Movement Biomechanics Group, Division of Physiotherapy, School of Health Professions, Bern University of Applied Sciences, Bern, Switzerland
[b] Department of Sport, Exercise and Health, University of Basel, Basel, Switzerland
[c] Orthopaedic Department, University Children's Hospital of Basel, Basel, Switzerland
[d] Faculty of Medicine, University of Basel, Basel, Switzerland

ARTICLE INFO

Keywords:
Biomechanics
Spine
Stoop
Squat
Agreement

ABSTRACT

Whole-body lifting strategies could be derived from conventional video recordings using the Stoop-Squat-Index, which quantifies the ratio between trunk forward lean and lower extremity joint flexion from 0 (full squat) to 100 (full stoop). The purpose of this study was to compare Stoop-Squat-Indices derived from conventional video recordings to those from a three-dimensional marker-based motion capture system and to evaluate interrater and intrarater reliability of the video-based approach.

Thirty healthy participants lifted a 5-kg box under different conditions (freestyle, squat, stoop). Kinematic data were recorded using a Vicon motion capture system (serving as reference standard) and an iPad camera. Stoop-Squat-Indices over the entire lifting cycle were derived separately from both approaches. Agreement was assessed using mean differences (video minus motion capture) and limits of agreement. Reliability was investigated by calculating intraclass correlation coefficients (ICC) and minimal detectable changes (MDC) over the course of the lifting cycle. Systematic errors were identified with Statistical Parametric Mapping-based T-tests.

Systematic errors between the video-based and the motion capture-based approach were observed among all conditions. Mean differences in Stoop-Squat-Indices over the lifting cycle ranged from −6.9 to 3.2 (freestyle), from −1.8 to 5.3 (squat) and from −2.8 to −1.1 (stoop). Limits of agreement were lower when the box was close to the floor, and higher towards upright standing. Reliability of the video-based approach was excellent for most of the lifting cycle, with ICC above 0.995 and MDC below 3.5.

These findings support using a video-based assessment of Stoop-Squat-Indices to quantify whole-body lifting strategy in field.

1. Introduction

Recent systematic reviews on lifting biomechanics have focused on investigating associations between lifting posture and low back pain (Nolan et al., 2020; Saraceni et al., 2020). Kinematic outcomes have not only included lumbar spine flexion and trunk forward bending angles (Saraceni et al., 2020) but also lower extremity joint angles and whole-body lifting strategy (Nolan et al., 2020). Whole-body lifting strategy has mostly been categorized into either stoop or squat (van Dieen et al., 1999). Other studies investigating whole-body lifting strategy have used a postural index, which is continuously scaled but calculated from multiple joint angles (Burgess-Limerick and Abernethy, 1997; Larivière et al., 2002), and hence requires high computational effort.

The Stoop-Squat-Index is a simple measure to assess whole-body lifting strategy by quantifying the ratio between forward lean of the trunk and the flexion of the lower extremity joints during lifting (Schmid, 2022). The index is calculated based on the vertical displacement of the spinous process C7 and the hip joint center and results in a value from 0 (full squat) to 100 (full stoop). It has previously been demonstrated to reliably discriminate between a squat and a stoop

* Corresponding author at: Spinal Movement Biomechanics Group, Division of Physiotherapy, School of Health Professions, Bern University of Applied Sciences, Murtenstrasse 10, 3008 Bern, Switzerland.
E-mail address: christian.bangerter@bfh.ch (C. Bangerter).

https://doi.org/10.1016/j.jbiomech.2024.111975
Accepted 29 January 2024
Available online 2 February 2024

movement throughout the entire lifting cycle, and has been used to investigate the association between whole-body lifting strategy and pain-related fear (Bangerter et al., 2023; Schmid et al., 2021; Schmid, 2022). A major advantage of the Stoop-Squat-Index is that it can be easily determined from conventional video recordings, allowing field assessments such as in occupational or clinical settings.

Most available studies on lifting biomechanics have been conducted in a laboratory setting (Saraceni et al., 2020), which may not allow direct conclusions for everyday lifting behavior. In addition, marker-based motion capture approaches are expensive, time-consuming, and do not allow for large-scale field observations. Previous studies have mostly only analyzed discrete parameters, such as range of motion or peak values (Nolan et al., 2020; Saraceni et al., 2020) but have not considered continuous data, which could have washed out possible differences. Recently, the advantage of analyzing continuous kinematic data over the entire lifting cycle has been pointed out to provide more detailed information about movement strategies (Papi et al., 2020). Correspondingly, agreement with reference methods and reliability analyses should not be limited to predefined time points but be assessed continuously over the entire lifting cycle (Schmid, 2022).

Therefore, the purpose of this study was to compare continuous Stoop-Squat-Indices derived from conventional video recordings to those obtained with a three-dimensional marker-based motion capture system and to evaluate the interrater and intrarater reliability of Stoop-Squat-Indices derived from video recordings.

2. Methods

2.1. Participants

Thirty healthy adults (19 females and 11 males) were enrolled [mean ± standard deviation (range); age: 32.5 ± 11.5 (19–57) years, height: 172.7 ± 6.8 (162–187) cm, mass: 69.0 ± 10.6 (50.8–89.0) kg, body mass index: 23.1 ± 3.0 (17.8–28.6) kg/m^2]. Inclusion criteria were: aged between 18 and 60 years and currently free of any sort of pain. Exclusion criteria were: a low back pain episode within the prior 6 months; pathologies, diseases, injuries, surgeries, painful conditions, or other circumstances limiting the capability of lifting; obesity (body mass index ≥ 30 kg/m^2); and insufficient understanding of German. Women with known current pregnancy as well as breastfeeding mothers were excluded. The responsible ethics committee provided exemption for this study (Kantonale Ethikkommission Bern, Req-2021–00878), and all participants gave written informed consent prior to data collection. This methods comparison and reliability study followed the Guidelines for Reporting Reliability and Agreement Studies (Kottner et al., 2011). The sample size of 30 participants was chosen following the respective recommendation for reliability studies (Koo and Li, 2016).

2.2. Data collection

2.2.1. Experimental procedure

All measurements were conducted by the same experienced physiotherapist in one single visit to the Bern Movement Laboratory. Following the collection of demographic and anthropometric data, participants were equipped with retro-reflective skin markers as previously described (Schmid et al., 2017). One additional marker was placed on the left greater trochanter (trochanter marker) to facilitate and standardize the subsequent video analyses (Damsted et al., 2015; Fernández-González et al., 2020). For this study, however, only the pelvis and lower body markers, the trochanter marker and the marker placed on the tip of the spinous process C7 (C7 marker) were considered.

Three-dimensional marker positions were recorded using a 16-camera Vicon motion capture system (Vicon, Oxford, UK; sampling frequency: 200 Hz). Conventional video recordings were conducted simultaneously using an iPad Air (Apple Inc., Cupertino, CA, USA; sampling frequency: 60 Hz) placed on a tripod at 85 cm above the floor and 3 m from the person perpendicular to the participant's lifting plane (strictly lateral view). No correction for potential projection errors was performed.

2.2.2. Lifting tasks

Participants were asked to repetitively lift up and put down a 5-kg box (40x20x10cm) at a self-selected speed under three conditions. In brief, the three conditions (Fig. 1, left) were freestyle (intuitively), squat (keeping the spine as upright as possible while flexing the knees) and stoop lifting (keeping the knees as straight as possible while bending the spine) (Dreischarf et al., 2016; von Arx et al., 2021). The first condition was always freestyle lifting, whereas the order of the remaining two lifting conditions was randomly assigned. To define the standing position with the feet in natural position hip width apart, the participant's toes were aligned to a tape stuck on the floor (frontal plane), and a perpendicular tape passing halfway between the participant's feet (sagittal plane). The box had handles, was equipped with two markers on the rim and placed on the floor 15 cm in front of the participant's toes (also marked with a tape). Each repetition started with the participant in an upright standing position, lifting up the box, maintaining the standing position for 1 s (Fig. 1, right), putting down the box, and returning to the standing position (without the box) (von Arx et al., 2021). For each condition, five valid (no marker loss, correct movement) trials were conducted.

2.2.3. Rating procedure

Raters involved in performing the video analyses were physiotherapists with no prior experience, knowledge, or particular interest in the field of video analysis. The same person introduced the software, informed all raters on how to perform the video analysis and provided a 30-minute supervised training for each rater. The order of participants to be analyzed was not randomized. Apart from the participant's body height and the video recordings, the raters had no further information about the participants but were aware of the purpose that their ratings would be used for comparisons. For the methods comparison, three raters were assigned to independently analyze all video recordings of one single lifting condition (either freestyle, squat, or stoop). For interrater reliability, two additional raters analyzed all freestyle lifting video recordings. For intrarater reliability, one rater repeated the analysis of all freestyle video recordings after 1 month.

2.3. Data processing

2.3.1. Video-based approach

Video recordings were processed using the Dartfish software (Dartfish company, Freiburg, Switzerland), according to a customized predefined protocol. The participant's body height was used as reference distance, and a virtual two-dimensional coordinate system was determined, with the origin at the T-intersection of the tape defining the standing position (Fig. 2, left). The start and end of each movement cycle were manually determined as the first frame with movement of the box and first frame with the box standing still on the floor, respectively. The C7 marker and the trochanter marker (serving as approximation of the hip joint center) were tagged in the first frame and selected for automatic tracking (Fig. 2, middle). The automatically tracked marker positions throughout the movement cycle were checked and manually adjusted in case of inaccuracy (at the discretion of each rater). Finally, the vertical positions of the two markers at each frame were exported as .csv file (Fig. 2, right). The end frame of the lifting-up cycle and the start frame of the putting-down cycle were identified based on the vertical position of the C7 marker using an event detection function in MATLAB (R2022a, MathWorks Inc., Natick, MA, USA) (Schmid, 2022; Suter et al., 2020).

2.3.2. Marker-based motion capture approach

Three-dimensional motion capture data were preprocessed using the

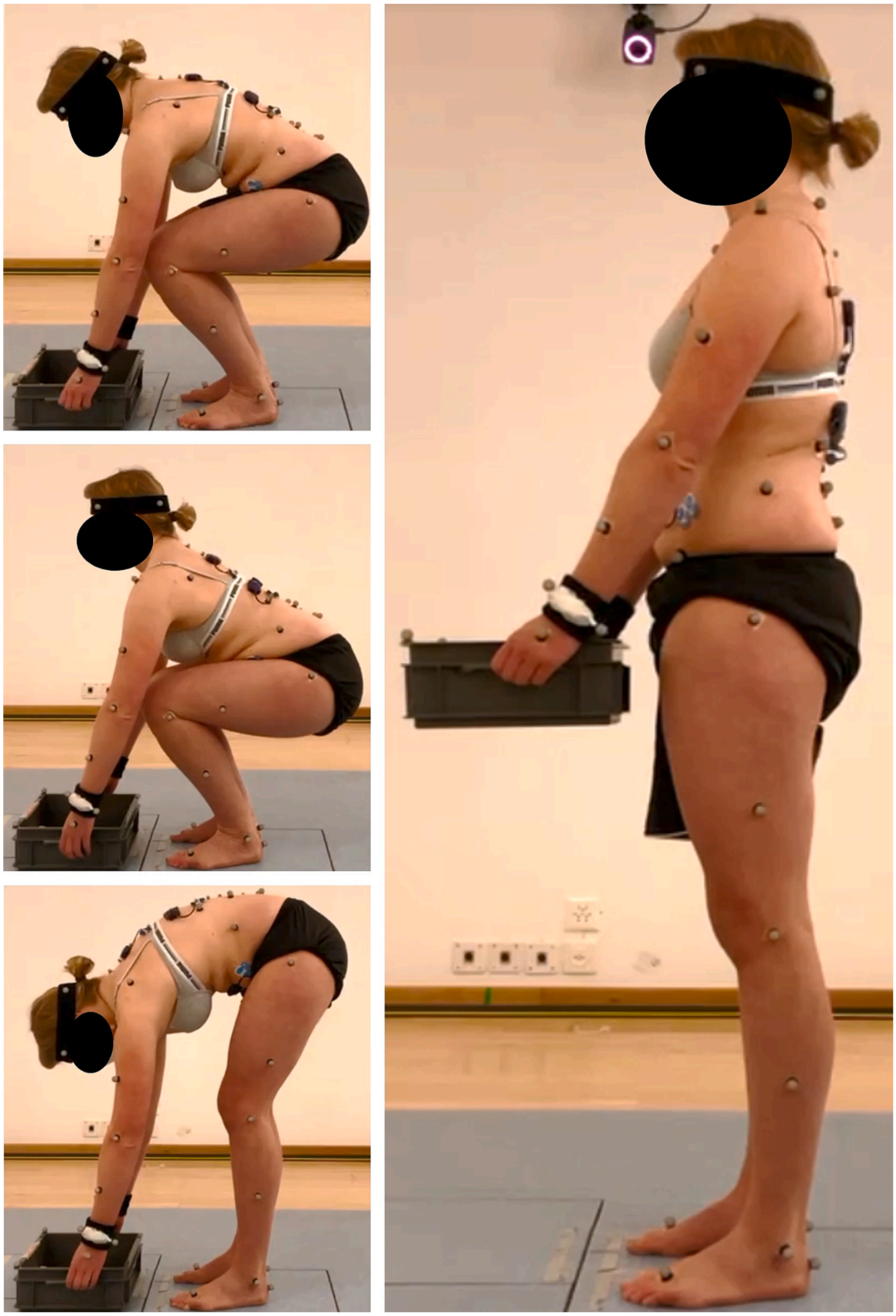

Fig. 1. Left: illustration of the different lifting conditions, including freestyle (top row), squat (middle row) and stoop (bottom row) lifting at the moment with the box on the floor (start of lifting-up and end of putting-down cycle). Right: upright standing position with holding the box (end of lifting-up and start of putting-down cycle). The attached electromyography-devices and additional markers were not considered in this study.

Nexus software (version 2.10.3, Vicon, Oxford, UK), and the hip joint center was calculated using the Plug-in Gait lower body model (Davis et al., 1991). Positions of the C7 marker, the left box marker and the hip joint center over the entire movement cycle were extracted. The start and end frames of the movement cycle were automatically identified using the vertical position of the left box marker (start lifting-up and end putting-down cycle) and the C7 marker (end lifting-up and start putting-down cycle) by an event detection function in MATLAB (Schmid, 2022; Suter et al., 2020).

2.4. Data reduction and statistics

Data from both approaches were further processed in MATLAB. All repetitions were separately time-normalized to 101 data points for the lifting-up and putting-down cycles, respectively. Thereafter, Stoop-Squat-Indices were calculated over the entire lifting cycles according to equation (1) (Schmid, 2022):

$$StSq = 100 - \left(\frac{(Vert\_HJC_{Standing} - Vert\_HJC_{Bending})*100}{Vert\_C7_{Standing} - Vert\_C7_{Bending}} \right) \quad (1)$$

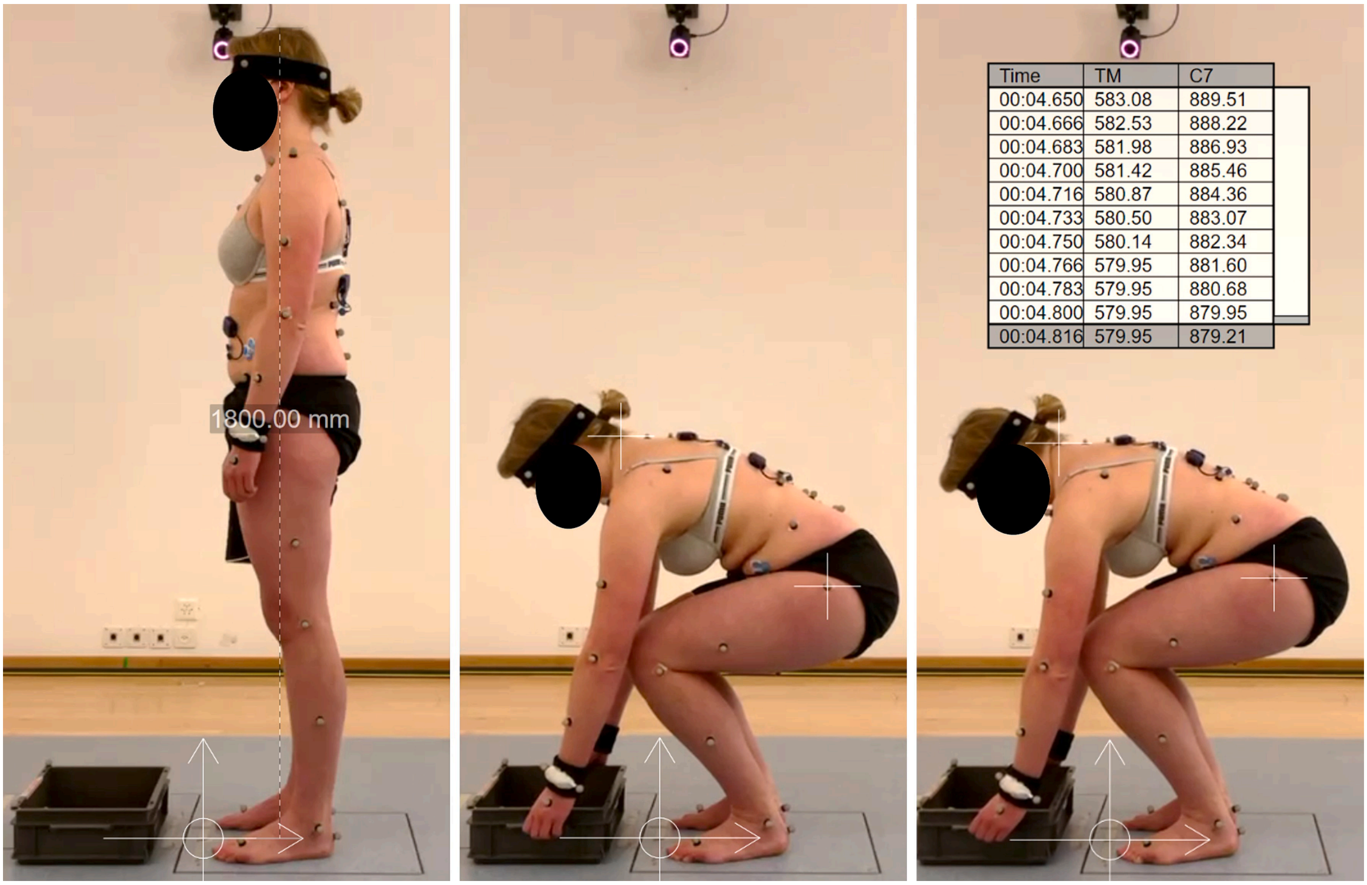

Fig. 2. Video-based approach to derive Stoop-Squat-Indices over the entire lifting cycle: determination of the reference distance and setting of the origin (left); definition of the start frame, tagging of the markers and selection for automatic tracking (middle); export of the vertical marker positions in a table over the entire lifting cycle (right).

The variables used for calculation of the Stoop-Squat-Index (StSq) were the vertical positions of the hip joint center (Vert_HJC) and the C7 spinous process (Vert_C7) during standing and bending (Schmid, 2022). Indices were averaged over the five trials per subject and condition. All statistical calculations were conducted with continuous data and comparisons were implemented using one-dimensional Statistical Parametric Mapping (SPM: spm1d-package, https://www.spm1d.org) in MATLAB (Pataky, 2012).

2.4.1. *Methods comparison*

To compare Stoop-Squat-Indices between the video-based and the motion capture-based approach (serving as reference standard), continuous Bland-Altman analyses (Bland and Altman, 2003; Suter et al., 2020) were conducted for each condition including mean differences (video-based minus motion capture-based method) and 95 % limits of agreement, both with 95 % confidence intervals (95 %CI) for each percentage of the movement cycle (Suter et al., 2020). Normal distribution of the differences was confirmed for the majority of the data using the SPM function *spm1d.stats.normality.ttest* (Pataky, 2012). If normal distribution was not confirmed for the entire lifting cycle, additional non-parametric tests were conducted to ensure that the results did not differ. To test whether the mean differences deviated statistically significantly from zero, one-sample T-tests (SPM function: *spm1d.stats.ttest*) (Pataky, 2012) were conducted (Suter et al., 2020) with a significance level of 0.05.

2.4.2. *Reliability*

To investigate interrater and intrarater reliability of the video-based approach, a three-layered procedure was conducted (Weir, 2005). First, systematic errors were identified by comparing mean differences between the raters (interrater reliability) or between the time points (intrarater reliability) to zero using one-sample T-tests in SPM (function: *spm1d.stats.ttest)* (Niggli et al., 2021; Pataky, 2012; Suter et al., 2020). Second, intraclass correlation coefficients (ICC) were calculated to evaluate relative reliability. Interrater reliability was assessed using a two-way random effects, single rater/measurement, consistency model (Koo and Li, 2016), whereas intrarater reliability was investigated using a two-way mixed-effects, single rater/measurement, agreement model (McGraw and Wong, 1996). ICC point estimates were defined as poor: $<$ 0.5, moderate 0.5–0.75, good: 0.75–0.9 and excellent: $>$0.9 and 95 %CI of the ICC estimates were calculated (Koo and Li, 2016). Third, minimal detectable changes (MDC) were calculated over the course of the lifting cycle as 1.96 times standard deviation of the differences (with 95 %CI) to investigate absolute reliability (Niggli et al., 2021; Suter et al., 2020; Weir, 2005).

3. Results

All 30 participants performed five valid repetitions for each lifting style, resulting in a total of 450 video and motion capture recordings (150 per condition) that were included in the methods comparison. Consequently, 150 freestyle video recordings were used for reliability assessment of the video-based approach.

3.1. *Methods comparison*

The agreement between the video-based and the motion capture-based assessment of the Stoop-Squat-Index was high (Figs. 3 to 5). The

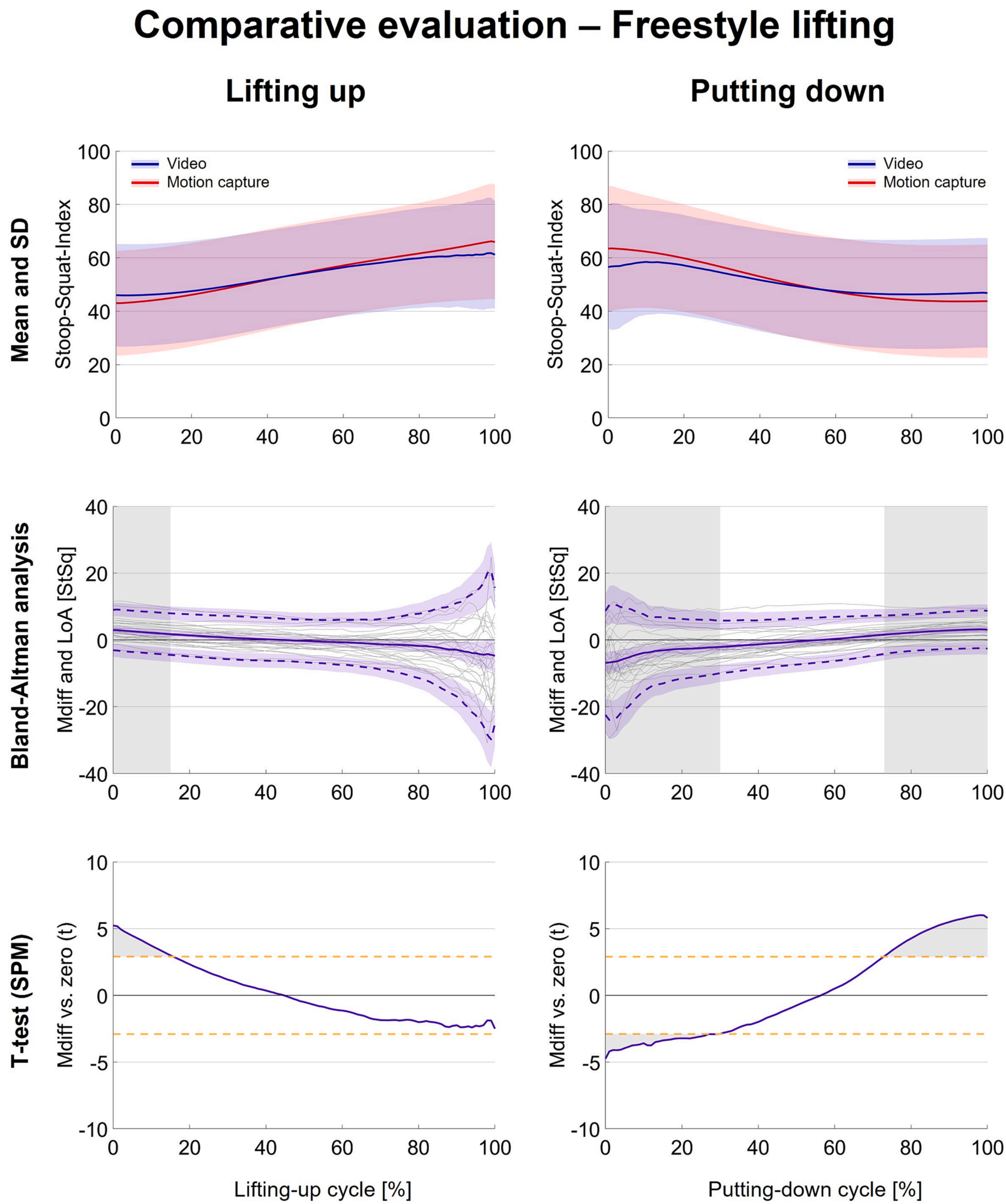

Fig. 3. Comparison between the video-based approach and the motion capture-based approach to derive Stoop-Squat-Indices during freestyle lifting for each percentage [%] of the lifting-up cycle (left column) and the putting-down cycle (right column). Top row: mean (solid lines) and standard deviation (SD, shaded areas) of Stoop-Squat-Indices from the video-based approach (blue) and the motion capture-based approach (red). Middle row: continuous Bland-Altman analyses with mean differences (Mdiff, purple solid lines) in Stoop-Squat-Indices (StSq) and 95 % limits of agreement (LoA, purple dashed lines) with 95 % confidence intervals (purple shaded areas). The gray single curves display the mean differences for each subject and the gray shaded areas indicate the periods with systematic errors between the two approaches. Bottom row: SPM-based one-sample T-test comparing the deviations of the mean differences to zero. The purple solid lines show the SPM t-curve, and the orange horizontal dashed lines display the threshold for statistical significance at an alpha-level of 0.05. The light gray shaded areas represent the supra-threshold clusters, indicating periods with statistically significant deviations of the mean differences from zero. SPM = Statistical Parametric Mapping. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

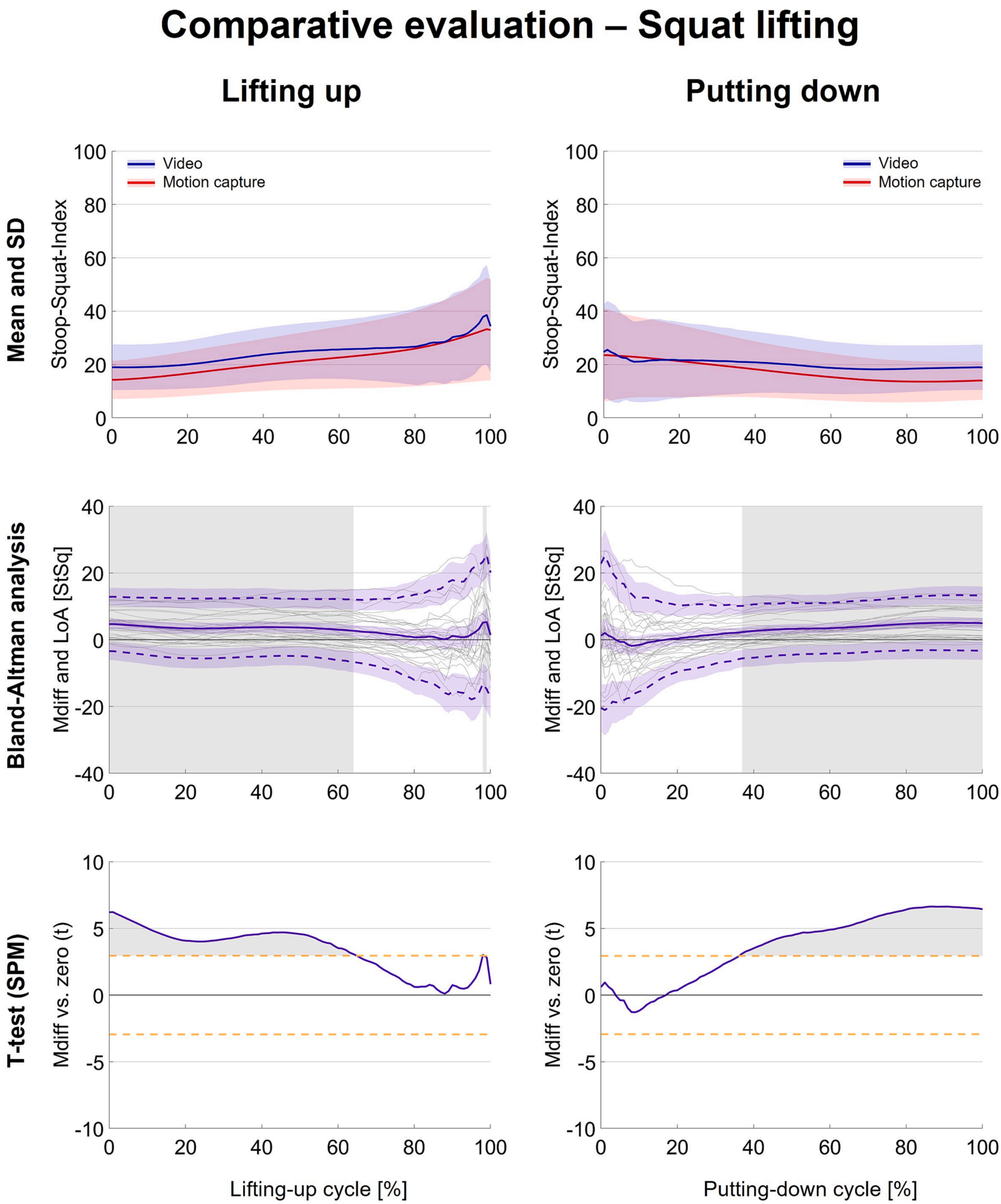

Fig. 4. Comparison between the video-based approach and the motion capture-based approach to derive Stoop-Squat-Indices during squat lifting for each percentage [%] of the lifting-up cycle (left column) and the putting-down cycle (right column). Top row: mean (solid lines) and standard deviation (SD, shaded areas) of Stoop-Squat-Indices from the video-based approach (blue) and the motion capture-based approach (red). Middle row: continuous Bland-Altman analyses with mean differences (Mdiff, purple solid lines) in Stoop-Squat-Indices (StSq) and 95 % limits of agreement (LoA, purple dashed lines) with 95 % confidence intervals (purple shaded areas). The gray single curves display the mean differences for each subject and the gray shaded areas indicate the periods with systematic errors between the two approaches. Bottom row: SPM-based one-sample T-test comparing the deviations of the mean differences to zero. The purple solid lines show the SPM t-curve, and the orange horizontal dashed lines display the threshold for statistical significance at an alpha-level of 0.05. The light gray shaded areas represent the supra-threshold clusters, indicating periods with statistically significant deviations of the mean differences from zero. SPM = Statistical Parametric Mapping. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

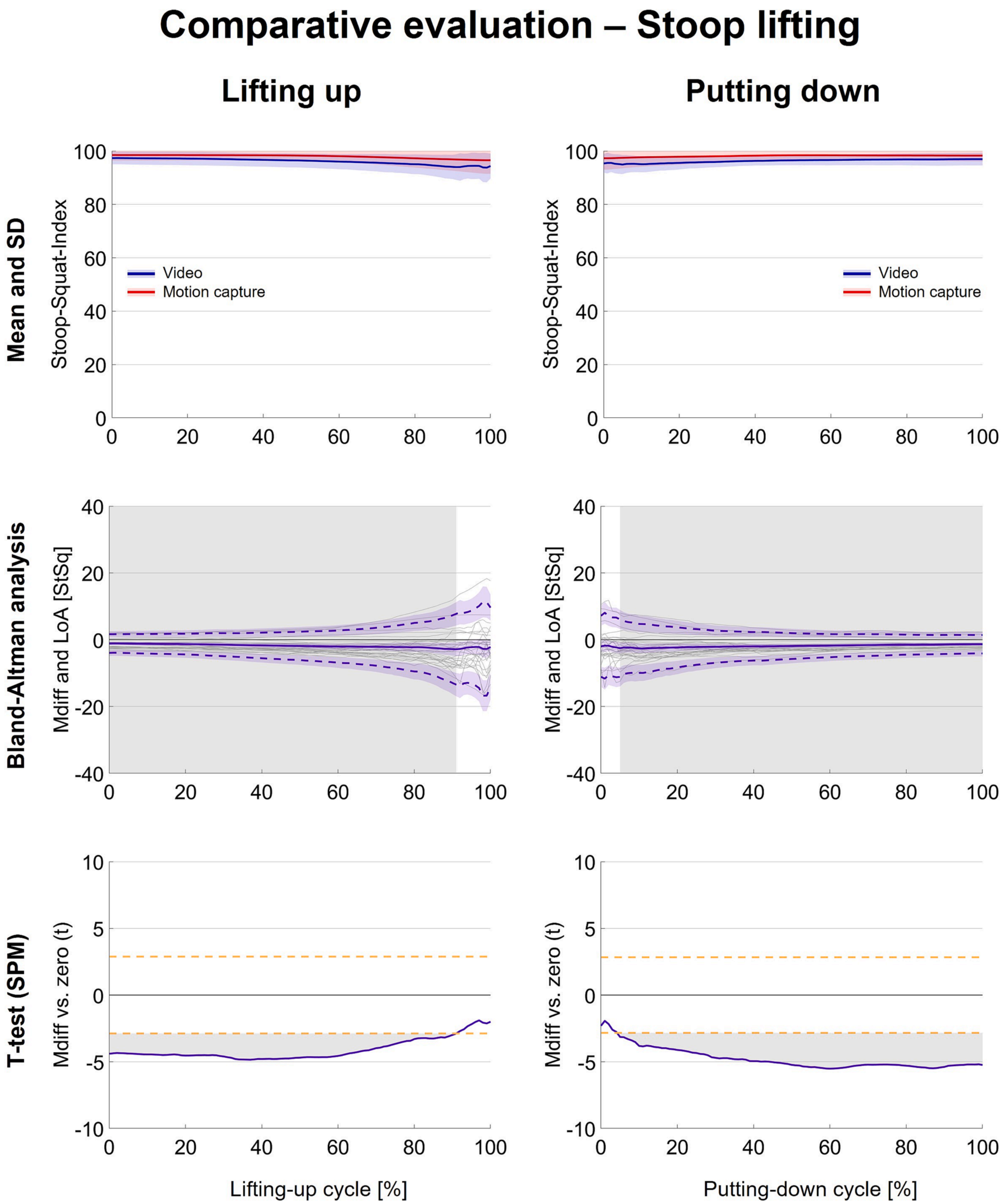

Fig. 5. Comparison between the video-based approach and the motion capture-based approach to derive Stoop-Squat-Indices during stoop lifting for each percentage [%] of the lifting-up cycle (left column) and the putting-down cycle (right column). Top row: mean (solid lines) and standard deviation (SD, shaded areas) of Stoop-Squat-Indices from the video-based approach (blue) and the motion capture-based approach (red). Middle row: continuous Bland-Altman analyses with mean differences (Mdiff, purple solid lines) in Stoop-Squat-Indices (StSq) and 95 % limits of agreement (LoA, purple dashed lines) with 95 % confidence intervals (purple shaded areas). The gray single curves display the mean differences for each subject and the gray shaded areas indicate the periods with systematic errors between the two approaches. Bottom row: SPM-based one-sample T-test comparing the deviations of the mean differences to zero. The purple solid lines show the SPM t-curve, and the orange horizontal dashed lines display the threshold for statistical significance at an alpha-level of 0.05. The light gray shaded areas represent the supra-threshold clusters, indicating periods with statistically significant deviations of the mean differences from zero. SPM = Statistical Parametric Mapping. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

SPM-based analysis demonstrated statistically significant mean differences from zero for freestyle, squat and stoop lifting. Mean differences were comparable between the periods with and without systematic errors (Table 1) and of similar magnitude as the within-subject standard deviation (Appendix 1). Mean differences in Stoop-Squat-Indices between the two approaches ranged from −6.9 to 3.2 for freestyle, from −1.8 to 5.3 for squat and from −2.8 to −1.1 for stoop lifting. Across all conditions, the limits of agreement were lower for the periods where the box was close to the floor, and higher towards upright standing, representing more variability and uncertainty within these periods (Figs. 3 to 5).

3.2. Reliability

We found excellent interrater (Fig. 6) and intrarater reliability (Fig. 7) for the video-based assessment of the Stoop-Squat-Index for most of the lifting cycle. Systematic errors were observed for interrater reliability (0–63 % of lifting-up cycle; 26–31 %, 49–52 % of putting-down cycle) and intrarater reliability (20–25 % of lifting-up cycle). Mean differences in Stoop-Squat-Indices between raters ranged from −0.6 to 0.7 and between time points from −0.5 to 1.8, respectively (Table 1). For the first 80 % of the lifting-up and the last 80 % of the putting-down cycle, reliability was excellent with slightly lower interrater reliability (ICC > 0.995, 95 %CI: 0.991–1.0, MDC < 3.5) than intrarater reliability (ICC > 0.997, 95 %CI: 0.994–1.0, MDC < 2.9). Within the late lifting-up (80–100 %) and the early putting-down cycle (0–20 %), the variability of the mean differences considerably increased, resulting in lower ICC and higher MDC within these periods (Figs. 6 and 7).

4. Discussion

The aim of this study was to compare continuous Stoop-Squat-Indices derived from conventional video recordings to those obtained with a three-dimensional marker-based motion capture system and to evaluate the interrater and intrarater reliability of Stoop-Squat-Indices derived from video recordings. We found high agreement between the video-based and the motion capture-based approach among all lifting conditions. Moreover, we observed excellent interrater and intrarater reliability of the video-based assessment for most of the lifting cycle.

4.1. Methods comparison

The increased uncertainty close to upright standing (70–100 % of lifting-up and 0–30 % of putting-down cycle) indicates a limited sensitivity of the Stoop-Squat-Index for these periods. Minor displacements of the C7 and trochanter marker strongly affect the resulting Stoop-Squat-Indices, which is why it should be interpreted with caution. Nonetheless, considering that lifting strategy is less important in almost upright standing positions, this restriction seems acceptable and of less clinical relevance. In fact, recent biomechanical literature has demonstrated that differences in lumbar loading among various lifting styles mainly occurred in the periods with the box close to the floor (first half of the lifting-up cycle) (von Arx et al., 2021). Moreover, peak moments during lifting were found to emerge shortly after lifting up the box, emphasizing the clinical relevance of this interval (Faber et al., 2009). To analyze discrete Stoop-Squat-Indices at a predefined moment in time we therefore suggest choosing an instance in the interval from 0 to 70 % for the lifting-up cycle and from 30 to 100 % for the putting-down cycle, respectively. Across all conditions, the mean differences in Stoop-Squat-Indices were small (mostly below 5) and of similar magnitude as the within-subject standard deviation of the respective condition. Therefore, these differences can be considered acceptable.

Furthermore, the video-based approach yielded systematically higher Stoop-Squat-Indices during squat and part of freestyle lifting of up to 5.3 and 3.2, respectively, indicating a bias of the video-based approach towards more stoop lifting behavior. The main explanation for this disagreement between the two methods could be the different approaches to define the position of the hip joint center. While for the motion capture approach, the vertical position of the hip joint center was calculated (Davis et al., 1991), its location was estimated using the vertical position of the trochanter marker in the video-based approach. The finding that differences between both methods increased in positions with pronounced hip flexion might partially be ascribed to soft tissue artifacts, which were identified to mainly affect a marker on the greater trochanter during active hip movement (Fiorentino et al., 2017). Thus, it can be assumed that the skin marker could not accurately replicate the backward/downward movement of the greater trochanter in positions with large hip flexion, resulting in an underestimation of its vertical displacement.

In upright standing position, trochanter-based methods to identify the position of the hip joint center were found to underestimate its actual vertical position of about 2 cm (Bennett et al., 2016; Kirkwood et al., 1999). Moreover, such approximations require an accurate palpation of the greater trochanter and a precise marker placement, which poses a notable source of error (Della Croce et al., 1999). However, since the Stoop-Squat-Index describes a proportion of vertical

Table 1
Range (minimum to maximum) of mean differences (video minus motion capture) in Stoop-Squat-Indices (StSq) for the periods of the lifting cycle with statistically significant mean differences from zero ($p \leq 0.05$) and the periods without statistically significant mean differences from zero ($p > 0.05$).

Comparison	Condition	Phase	Number of supra-threshold clusters	Statistically significant mean difference from zero ($p \leq 0.05$)			p-value	No statistically significant mean difference from zero ($p > 0.05$)		
				Lifting cycle [%]	Mean differences [StSq]			Lifting cycle [%]	Mean differences [StSq]	
					from	to			from	to
Agreement	Freestyle	up	1	0–15	1.7	3.0	0.024	16–100	–4.7	1.7
		down	2	0–30	–6.9	–2.1	0.004	31–72	–2.0	1.5
				73–100	1.6	3.2	0.006			
	Squat	up	2	0–64	2.7	4.7	< 0.001	65–97	0.1	3.3
				98	5.1	5.1	0.05	99–100	1.4	5.3
		down	1	37–100	2.3	5.1	< 0.001	0–36	–1.8	2.1
	Stoop	up	1	0–91	–2.8	–1.1	< 0.001	92–100	–2.8	–2.2
		down	1	5–100	–2.6	–1.3	< 0.001	0–4	–2.3	–1.8
Interrater reliability	Freestyle	up	1	0–63	–0.5	–0.2	< 0.001	64–100	–0.6	0.1
		down	2	26–31	–0.4	–0.4	0.024	0–25	–0.4	0.7
				49–52	–0.3	–0.3	0.035	32–48	–0.4	–0.3
								53–100	–0.3	0.1
Intrarater reliability	Freestyle	up	1	20–25	–0.2	–0.2	0.003	0–19	–0.2	0
								26–100	–0.5	0.4
		down	–	–	–	–	–	0–100	–0.1	1.8

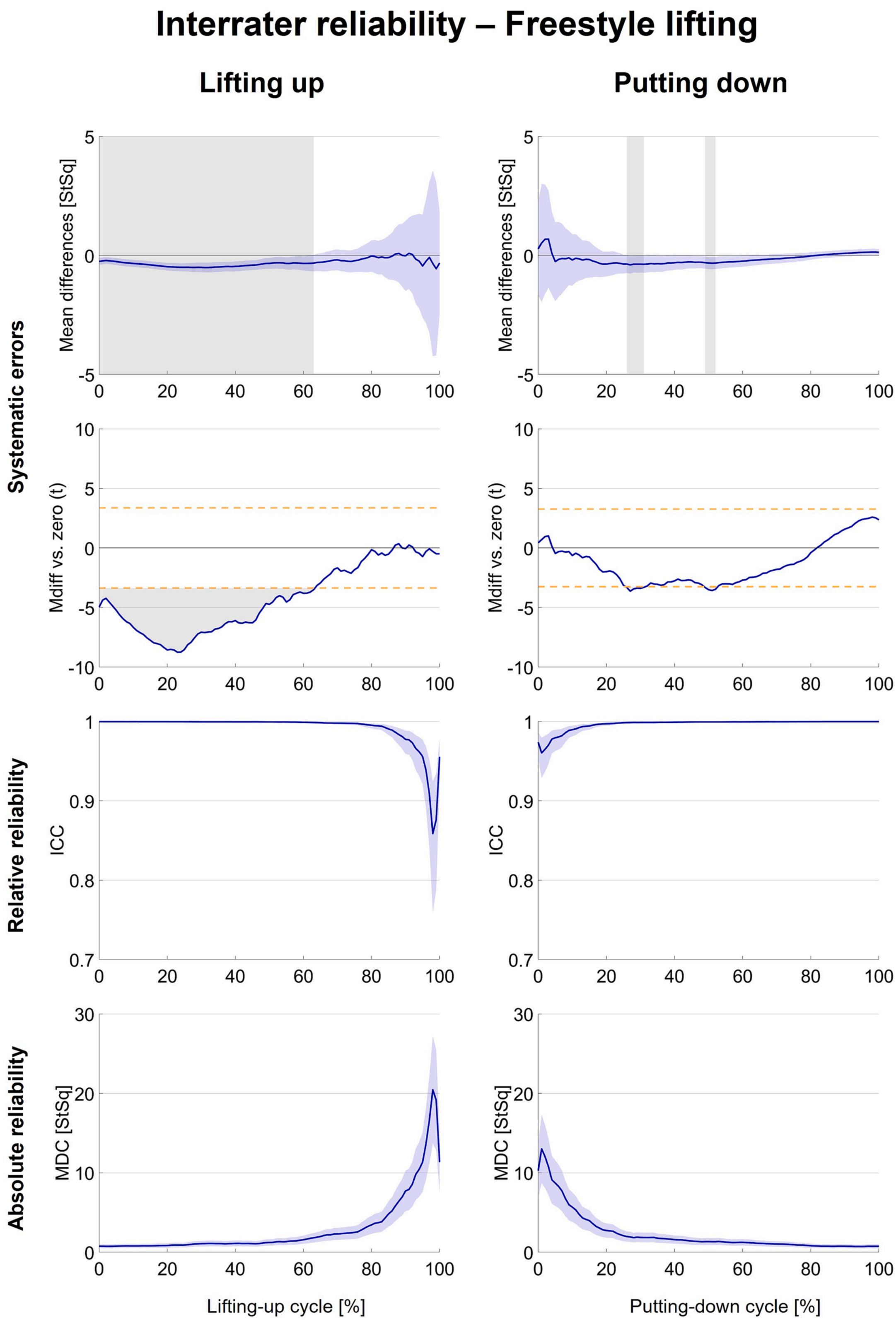

Fig. 6. Interrater reliability of the video-based approach to derive Stoop-Squat-Indices during freestyle lifting for each percentage [%] of the lifting-up cycle (left column) and the putting-down cycle (right column). Top row: Mean differences (blue solid lines) in Stoop-Squat-Indices (StSq) with 95 % confidence intervals (blue shaded areas). The gray shaded areas indicate the periods with systematic errors between the raters. Second row: SPM-based one-sample T-test comparing the deviations of the mean differences (Mdiff) to zero. The blue solid lines show the SPM t-curve, and the orange horizontal dashed lines display the threshold for statistical significance at an alpha-level of 0.05. The light gray shaded areas represent the supra-threshold clusters, indicating periods with statistically significant deviations of the mean differences from zero. Third row: point estimates of the intraclass correlation coefficients (ICC, blue solid lines) and 95 % confidence intervals (blue shaded areas). Bottom row: minimal detectable changes (MDC, blue solid lines) in Stoop-Squat-Indices (StSq) and 95 % confidence intervals (blue shaded areas). SPM = Statistical Parametric Mapping. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

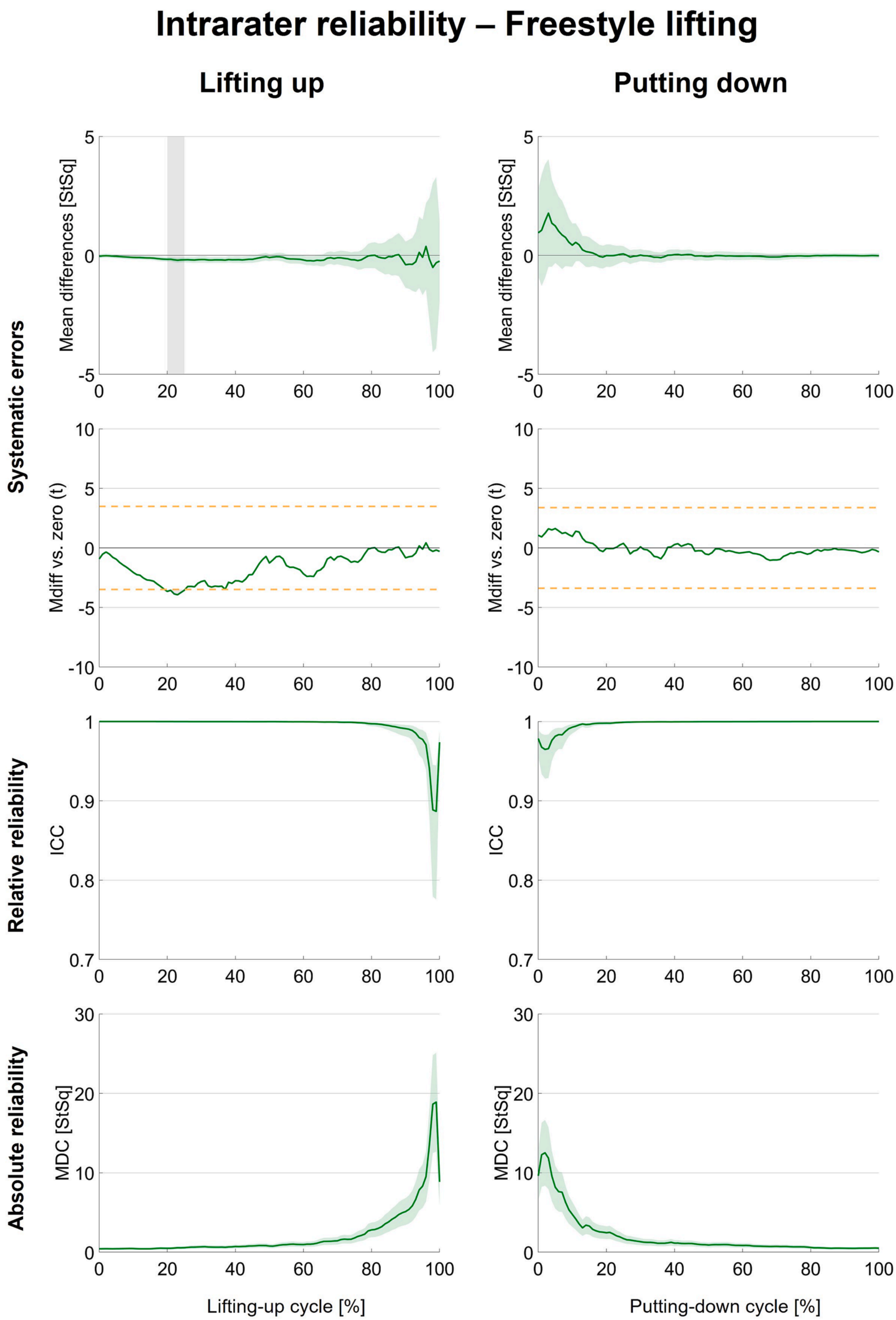

Fig. 7. Intrarater reliability of the video-based approach to derive Stoop-Squat-Indices during freestyle lifting for each percentage [%] of the lifting-up cycle (left column) and the putting-down cycle (right column). Top row: Mean differences (green solid lines) in Stoop-Squat-Indices (StSq) with 95 % confidence intervals (green shaded areas). The gray shaded areas indicate the periods with systematic errors between the time points. Second row: SPM-based one-sample T-test comparing the deviations of the mean differences (Mdiff) to zero. The green solid lines show the SPM t-curve, and the orange horizontal dashed lines display the threshold for statistical significance at an alpha-level of 0.05. The light gray shaded areas represent the supra-threshold clusters, indicating periods with statistically significant deviations of the mean differences from zero. Third row: point estimates of the intraclass correlation coefficients (ICC, green solid lines) and 95 % confidence intervals (green shaded areas). Bottom row: minimal detectable changes (MDC, green solid lines) in Stoop-Squat-Indices (StSq) and 95 % confidence intervals (green shaded areas). SPM = Statistical Parametric Mapping. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

marker displacements, inaccuracies related to marker placement and hip joint center identification in the upright standing position may be negligible.

For stoop lifting, the video-based approach yielded systematically lower Stoop-Squat-Indices of up to 2.8 compared to the motion capture-based approach. This disagreement can be explained by different distances of the analyzed markers from the camera. During stoop lifting, the trochanter marker only adopted small vertical displacement, was seen perpendicular, and located closer to the camera than the C7 marker. The greater distance of the C7 marker from the camera might have resulted in an underestimation of the C7 marker displacement in the video-based approach during stoop lifting, resulting in lower Stoop-Squat-Indices compared to the motion capture approach.

4.2. Reliability

Interrater and intrarater reliability were excellent, except for the 20 % of lifting cycle close to upright standing. The fact that reliability decreased within these periods could be evidence of the above-mentioned limited sensitivity of the Stoop-Squat-Index in almost upright standing positions. Although systematic errors between the raters and between the time points were observed, mean differences in Stoop-Squat-Indices remained below 1.8 for the entire lifting cycle. These slight differences within the video-based assessment seem reasonable and could be attributed to data processing inaccuracies regarding the visual determination of the start or end frame as well as the manual marker adjustment (e.g. in case of marker occlusion or inaccurate automatic marker tracking). During most of the lifting cycle (first 80 % of lifting-up and last 80 % of putting-down), the lower limits of the ICC 95 %CI were consistently above 0.99, indicating excellent relative reliability. Moreover, MDC within these periods were below 3.5 between raters and below 2.9 between time points.

4.3. Strengths and limitations

The use of SPM is a strength of this study, because this method enabled to investigate agreement and reliability over the entire lifting cycles without restricting comparisons to specific instances in time (Papi et al., 2020). The SPM-based analysis revealed considerable time-specific differences among these quality measures, which are valuable for interpretating Stoop-Squat-Indices. Another strength is that participants were asked to lift under different conditions, allowing to compare Stoop-Squat-Indices from both approaches over its entire range. Moreover, the structured protocol that was strictly followed during data collection and analysis to ensure a standardized and consistent procedure is a strength of this study. Namely, all measurements were conducted by the same experienced physiotherapist, the tripod holding the camera was always placed at the same position and skin markers were used to standardize the video-based analysis (Damsted et al., 2015; Fernández-González et al., 2020). The lack of synchronization between the video-based and the motion capture-based approach can be considered a limitation of this study. However, the respective temporal events could easily be identified based on the box movement allowing an independent determination of Stoop-Squat-Indices for each approach and should only marginally have influenced the results. The determination of absolute distances from conventional video recordings is prone to errors related to the distances between the camera and the markers, changes in the view angle and projection errors. To avoid additional computational effort, we did not correct for any of these possible error sources, which can be considered as limitation. However, since the Stoop-Squat-Index provides information on the ratio of the marker displacements, these shortcomings should not have had a large impact on the results. The order of participants to be analyzed was not randomized, so that the data might be biased with a training effect. This study only included a sample of healthy pain-free participants. Thus, the results can not directly be extrapolated to other populations. All raters were physiotherapists but the simplicity of the proposed video-based assessment and the fact that all raters without experience in video analysis practiced for only 30 min suggest that the results could also apply to other rater populations. Since our values for intrarater reliability are only based on one repeated measure of one rater, it cannot be excluded that factors such as training, experience or boredom could influence this measure.

4.4. Potential applications

The main advantage of the proposed video-based approach is that it enables to efficiently quantify whole-body lifting strategy with low expenditure outside a laboratory setting. As the Stoop-Squat-Index does not provide any information regarding spinal motion, it has been recommended to use the index along with a wearable system to additionally quantify spinal motion to provide comprehensive information about lifting behavior in an occupational setting (Schmid, 2022).

5. Conclusion

This study demonstrates that a video-based assessment of the Stoop-Squat-Index to quantify whole-body lifting strategy represents an accurate and reliable method compared to a motion capture approach. These findings endorse the use of the proposed video-based approach outside a laboratory setting in the context of large-scale field measurements or within a clinical setting.

CRediT authorship contribution statement

Christian Bangerter: Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Oliver Faude:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Patric Eichelberger:** Writing – review & editing, Software, Resources, Methodology, Data curation. **Annina Schwarzentrub:** Writing – review & editing, Investigation. **Milène Girardin:** Writing – review & editing, Investigation. **Aglaja Busch:** Writing – review & editing, Methodology. **Carol-Claudius Hasler:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Stefan Schmid:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank the Bern University of Applied Sciences, Switzerland, for financial support (Start-up grant for doctoral studies). Moreover, the authors thank Anja Schmid, Corina Venzin, Giovanna John, Martina Stadelmann and Panka Nagy for their assistance in processing the data.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2024.111975.

References

Bangerter, C., Meier, M.L., von Arx, M., Liechti, M., Schmid, S., 2023. Associations between pain-related fear and object lifting biomechanics are likely dependent on object weight. Proceedings of the World Physiotherapy Congress (WCPT) 2023, Dubai, United Arab Emirates.

Bennett, H.J., Shen, G., Weinhandl, J.T., Zhang, S., 2016. Validation of the greater trochanter method with radiographic measurements of frontal plane hip joint centers and knee mechanical axis angles and two other hip joint center methods. J. Biomech. 49, 3047–3051.
Bland, J.M., Altman, D.G., 2003. Applying the right statistics. analyses of measurement studies. Ultrasound. Obstet. Gynecol. 22, 85–93.
Burgess-Limerick, R., Abernethy, B., 1997. Toward a quantitative definition of manual lifting postures. Hum. Factors: J. Hum. Factors Ergon. Soc. 39, 141–148.
Damsted, C., Nielsen, R.O., Larsen, L.H., 2015. Reliability of video-based quantification of the knee- and hip angle at foot strike during running. Int. J. Sports Phys. Ther. 10, 147–154.
Davis, R.B., Õunpuu, S., Tyburski, D., Gage, J.R., 1991. A gait analysis data collection and reduction technique. Hum. Mov. Sci. 10, 575–587.
Della Croce, U., Cappozzo, A., Kerrigan, D.C., 1999. Pelvis and lower limb anatomical landmark calibration precision and its propagation to bone geometry and joint angles. Med. Biol. Eng. Compu. 37, 155–161.
Dreischarf, M., Rohlmann, A., Graichen, F., Bergmann, G., Schmidt, H., 2016. In vivo loads on a vertebral body replacement during different lifting techniques. J. Biomech. 49, 890–895.
Faber, G.S., Kingma, I., Bakker, A.J.M., van Dieën, J.H., 2009. Low-back loading in lifting two loads beside the body compared to lifting one load in front of the body. J. Biomech. 42, 35–41.
Fernández-González, P., Koutsou, A., Cuesta-Gómez, A., Carratalá-Tejada, M., Miangolarra-Page, J.C., Molina-Rueda, F., 2020. Reliability of Kinovea® Software and Agreement with a Three-Dimensional Motion System for Gait Analysis in Healthy Subjects. Sensors (Basel) 20.
Fiorentino, N.M., Atkins, P.R., Kutschke, M.J., Goebel, J.M., Foreman, K.B., Anderson, A. E., 2017. Soft tissue artifact causes significant errors in the calculation of joint angles and range of motion at the hip. Gait Posture 55, 184–190.
Kirkwood, R.N., Culham, E.G., Costigan, P., 1999. Radiographic and non-invasive determination of the hip joint center location: effect on hip joint moments. Clin. Biomech. 14, 227–235.
Koo, T.K., Li, M.Y., 2016. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. J. Chiropr. Med. 15, 155–163.
Kottner, J., Audigé, L., Brorson, S., Donner, A., Gajewski, B.J., Hróbjartsson, A., Roberts, C., Shoukri, M., Streiner, D.L., 2011. Guidelines for Reporting Reliability and Agreement Studies (GRRAS) were proposed. J. Clin. Epidemiol. 64, 96–106.
Larivière, C., Gagnon, D., Loisel, P., 2002. A biomechanical comparison of lifting techniques between subjects with and without chronic low back pain during freestyle lifting and lowering tasks. Clin. Biomech. 17, 89–98.
McGraw, K.O., Wong, S.P., 1996. Forming inferences about some intraclass correlation coefficients. Psychol. Methods 1, 30–46.
Niggli, L.A., Eichelberger, P., Bangerter, C., Baur, H., Schmid, S., 2021. Between-session reliability of skin marker-derived spinal kinematics during functional activities. Gait Posture 85, 280–284.
Nolan, D., O'Sullivan, K., Newton, C., Singh, G., Smith, B.E., 2020. Are there differences in lifting technique between those with and without low back pain? A systematic review. Scand. J. Pain 20, 215–227.
Papi, E., Bull, A.M.J., McGregor, A.H., 2020. Alteration of movement patterns in low back pain assessed by Statistical Parametric Mapping. J. Biomech. 100, 109597.
Pataky, T.C., 2012. One-dimensional statistical parametric mapping in Python. Comput. Methods Biomech. Biomed. Engin. 15, 295–301.
Saraceni, N., Kent, P., Ng, L., Campbell, A., Straker, L., O'Sullivan, P., 2020. To flex or not to flex? Is there a relationship between lumbar spine flexion during lifting and low back pain? A systematic review with meta-analysis. J. Orthop. Sports Phys. Ther. 50, 121–130.
Schmid, S., 2022. The Stoop-Squat-Index: a simple but powerful measure for quantifying whole-body lifting behavior. Arch. Physiother. 12, 8.
Schmid, S., Bruhin, B., Ignasiak, D., Romkes, J., Taylor, W.R., Ferguson, S.J., Brunner, R., Lorenzetti, S., 2017. Spinal kinematics during gait in healthy individuals across different age groups. Hum. Mov. Sci. 54, 73–81.
Schmid, S., Bangerter, C., Suter, M., Meier, M.L., 2021. Fear-avoidance beliefs are not related to stoop-squat-behavior during object lifting in healthy pain-free adults. Proceedings of the XXVIII Congress of the International Society of Biomechanics (ISB), Stockholm, Sweden, 2021.
Suter, M., Eichelberger, P., Frangi, J., Simonet, E., Baur, H., Schmid, S., 2020. Measuring lumbar back motion during functional activities using a portable strain gauge sensor-based system. A comparative evaluation and reliability study. J. Biomech. 100, 109593.
van Dieen, J.H., Hoozemans, M.J., Toussaint, H.M., 1999. Stoop or squat. a review of biomechanical studies on lifting technique. Clin. Biomech. (Bristol, Avon) 14, 685–696.
von Arx, M., Liechti, M., Connolly, L., Bangerter, C., Meier, M.L., Schmid, S., 2021. From Stoop to Squat: A comprehensive analysis of lumbar loading among different lifting styles. Front. Bioeng. Biotechnol. 9, 769117.
Weir, J.P., 2005. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J. Strength Cond. Res. 19, 231–240.