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RESEARCH ARTICLE

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Gender and body height discriminate spinal movement patterns during lifting and lowering tasks

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ABSTRACT

This study aimed to explore the relationships between gender, anthropometrics, and spinal movement patterns (SMP) during lifting and lowering tasks. Thirty adults lifted and lowered a 15 kg-box using a freestyle, squat, and stoop technique. A stepwise segmentation approach, along with the timing of main inflection points of relative angles, was used to distinguish various spinal movement patterns. Temporal multi-segmental interactions were categorised, and their frequencies were analysed based on segments and lifting techniques. SMP's demonstrated varying associations with gender and anthropometric factors during lifting and lowering phases. Notably, during stoop lifting, females tended towards a bottom-up pattern, contrasting with males' preference for a simultaneous pattern. Cluster analysis highlighted the bottom-up pattern in the thoracic spine as the most prominent discriminating factor among females. This SMP categorisation method holds potential for designing tailored manual material handling strategies and re-evaluating therapeutic and exercise programs in occupational, clinical, and sport contexts.

Practitioner Summary: There is little information about multi-segmental spinal movement pattern and its relation to individual characteristics during lifting and lowering. Based on the results of this experimental study, gender, height, technique and their combinations could influence spinal movement pattern and be used for designing more subject-specific exercise programs in ergonomic settings.

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KEYWORDS
Anthropometry; spine; pattern frequency; stepwise segmentation; object lifting

Introduction

The normal pattern of spinal motion is not well understood, and defining abnormal movement has been difficult (Zwambag et al. 2019). Movement adaptation or abnormality in any part of the musculoskeletal system can be defined by understanding normal function, particularly in the case of the spine, which is a complex system (Prins et al. 2018). A recent investigation of isolated spinal flexion and extension in young healthy males showed different spatiotemporal movement strategies, with movements being initiated top-down, bottom-up and simultaneously (Beaudette et al. 2019). In clinical evaluations, observations of spinal movement patterns have been used to characterise patients with low back pain (LBP) (Gatton and Pearcy 1999, Pranata et al. 2018). Some studies have reported changes in kinematic variables, such as a delay in the occurrence of peak trunk angle and acceleration (Ferguson et al. 2004), increased thoracic flexion angle (Larivière, Gagnon, and Loisel 2000), and early thoracic extension (Wrigley et al. 2005) during lifting. However, there is little information about multi-segmental spinal movement pattern and its relation to individual characteristics such as gender and anthropometrics during lifting and lowering.

It was shown that individuals adopt a lifting technique based on personal and task characteristics such as age (Boocock, Mawston, and Taylor 2015), gender (Plamondon et al. 2014, Sheppard, Stevenson, and Graham 2016), anthropometry (Burgess-Limerick and Abernethy 1997), LBP (Straker 2003), muscle strength (Kang and Xudong 2010), level of experience (Plamondon et al. 2014, Riley et al. 2015), load mass (Hoozemans et al. 2008, Sheppard, Stevenson, and Graham 2016), task repetition and duration (Bonato et al. 2003, Mehta, Lavender, and Jagacinski 2014), load size (Kingma, Van Dieën, and Toussaint 2005), and position (Wilke et al. 1999, Hoozemans et al. 2008). Despite the fact that most studies have focused on

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spatial variables, there is controversy regarding the lower back load and lumbar angle of any lifting style (van Dieen et al. 1999, Khoddam-Khorasani, Arjmand, and Shirazi-Adl 2020, Von Arx et al. 2021).

Gender and anthropometrics are considered to be associated with LBP (Cholewicki et al. 2005, Hoy et al. 2012, Lidar et al. 2012, Mikkonen et al. 2013, Yang and Haldeman 2018). Females experience more load on the lower back during object lifting due to more hip–pelvic motion than males with preferred trunk motion (Lindbeck and Kjellberg 2001, Marras, Davis, and Jorgensen 2002). Among manual material handlers, experienced females showed sequential motion (i.e. knee, hip, and back), while males demonstrated more synchronised motion. Additionally, females utilise lumbar passive tissues and recruit leg lifting strategies, while males prefer back lifting (i.e. stoop style) (Plamondon et al. 2014, Gagnon, Plamondon, and Larivière 2018). However, apart from manual material handlers, both males and females adopt a similar lifting strategy by increasing normalised loads (based on maximum isometric back strength) (Sheppard, Stevenson, and Graham 2016). There is some evidence that reveals the relationship between anthropometrics (e.g. mass and height) and lifting styles, i.e. it seems that taller and heavier participants prefer a stoop lifting style (Burgess-Limerick and Abernethy 1997). Thus, exploring spinal movement patterns that are related to the aforementioned parameters may help to better understand individual biomechanical advantages and disadvantages during manual handling tasks.

Variability in quantitative assessment, both between and within subjects, can sometimes pose an obstacle to reaching a definitive statistical conclusion (Gatton and Pearcy 1999, Preuss and Popovic 2010). Lower variability creates a more favourable scenario for comparing studies and evaluating interventions. In fact, numerous statistical tests are responsive to variability (Altman and Bland 2003, Giuliano and Polanowicz 2008), and achieving significance in statistical tests can be challenging. Hence, categorising movement strategies might be useful to better handle between and within-subjects variability. Temporal multi-segmental interactions have previously been categorised as occurring in a 1) simultaneous (SIM), 2) top-down (T-D), or 3) bottom-up (B-U) manner (Harada et al. 2000, Takayanagi et al. 2001, Ignasiak, Rüeger, and Ferguson 2017).

To assess interactions among spinal segments, it is believed that determining the effects of each individual element (defined segments) on the entire spinal system yields valuable information. In the stepwise segmentation approach (Nematimoez and Thomas 2022), the contribution of each segment is considered by including or excluding it from the relative angle and its derivative calculations; thus, any changes in these variables can reveal the effects of a given segment on the system. In cases of spinal flexion/extension and lifting/lowering tasks, timing of the main inflection points (TMIP) provides information about temporal interaction (i.e. SIM, T-D, and B-U) among defined segments (Nematimoez, Breen, and Breen 2023); this timing variable is sensitive to the contribution of a segment when conducting stepwise segmentation analysis. For example, by restricting upper thoracic movement and its contribution to lifting tasks, stepwise segmentation analysis has shown temporal latencies in the main inflection points (Nematimoez and Thomas 2022).

The primary aim of this retrospective data analysis was to identify possible associations between individual participant characteristics (i.e. gender, mass, and height) and spinal movement patterns during lifting and lowering of an object with different techniques. The secondary aim was to investigate the potential of spinal movement patterns as a variable to characterise the participants regarding their gender (male and female) using an unsupervised machine learning algorithm.

Materials and methods

Dataset

For this retrospective data analysis, motion capture data from thirty healthy and pain-free adults (males: 20, age: 29.7 ± 4.7 years, mass: 76.1 ± 7.4 kg, height: 178.4 ± 5.8 cm, body mass index (BMI): 23.9 ± 2.3 kg/m^2; females: 10, age: 36.1 ± 12.5 years, mass: 62.9 ± 9.3 kg, height: 169.1 ± 6.9 cm, BMI: 21.9 ± 2.2 kg/m^2) were included. The data were collected in the context of a previous study (Von Arx et al. 2021), for which the local ethics committee provided exemption. The main inclusion criteria were an age between 18 and 65 years, a BMI below 30 kg/m^2, no known spinal pathologies, previous spinal surgeries or musculoskeletal injuries that would have limited normal physical function, and no LBP episodes within the 6 months prior to data collection. Participants repetitively lifted and lowered a 15-kg-box (dimensions: 40 × 20 x 10 cm; height of handles: 8 cm above floor level) at a self-selected normal speed, using first a freestyle, then a squat and finally a stoop lifting technique (five repetitions per technique, resulting in a total of 15 lifting and 15 lowering movements per participant). A lifting and lowering sequence comprised unloaded upright stance, bending to grasp

the box, lifting it, holding it briefly in upright stance, lowering it, and returning to unloaded upright stance. Before commencing the next sequence, participants rested in unloaded upright stance for 5 to 10 seconds. The box mass was selected based on the Swiss National Accident Insurance Fund (SUVA) guidelines, which deem 15 kg safe for adults of all genders. For a detailed representation of the spine, participants were equipped with a previously described full-body marker set (Schmid et al. 2017), including 13 markers placed on the spinous processes of the vertebrae C7, T3, T5, T7, T9, T11, L1-5 as well as on the posterior superior iliac spines (PSIS). Marker data were collected at a rate of 200 Hz using a 16-camera optoelectronic motion capture system (Vicon, Oxford, UK).

Stepwise segmentation approach

To distinguish different spinal movement patterns, we used a stepwise segmentation approach implemented with custom MATLAB routines (MathWorks Inc., Natick, US). This first included the definition of eleven spinal segments, each consisting of the left and right PSIS markers as well as one of the spinous process markers (i.e. C7, T3, T5, T7, T9, T11, L1, L2, L3, L4, and L5). Based on these eleven segments, ten relative angles (i.e. L4-L5, L3-L5, L2-L5, L1-L5, T11-L5, T9-L5, T7-L5, T5-L5, T3-L5, and C7-L5) were computed (Eq. 1.1 and 1.2) and filtered using a 3 Hz low pass filter (second order, dual-pass Butterworth) (Nematimoez and Thomas 2022). Subsequently, we calculated the first derivatives of the filtered relative angles (Eq. 1.3), identified the lifting and lowering phases based on the vertical velocity of the markers placed on the box, and time normalised the data for each of the phases to 101 data points (0-100%).

$$RA_{Upper\,Segment-L5} = R_{Upper\,Segment} R_{L5} \tag{1.1}$$

$$RA_{Upper\,Segment-L5} = \begin{bmatrix} i_x & i_y & i_z \\ j_x & j_y & j_z \\ k_x & k_y & k_z \end{bmatrix}_{Upper\,Segment} \times \begin{bmatrix} i_x & j_x & k_x \\ i_y & j_y & k_y \\ i_z & j_z & k_z \end{bmatrix}_{L5} \tag{1.2}$$

$$1stD_{Upper\,Segment-L5} = RA_{Upper\,Segment-L5} \tag{1.3}$$

Where $RA_{Upper\,Segment-L5}$ are the relative angles of the upper segments (i.e. C7, T3, T5, T7, T9, T11, L1, L2, L3, and L4) versus L5; $R_{Upper\,Segment}$ are the local coordinate systems of the upper segments; R_{L5} is the transpose of the L5 local coordinate system; *i, j,* and *k* are unit vectors; *x, y,* and *z* are components of the three-dimensional coordinate system; and 1*stD* is the first derivative of the relative angle.

In a final step, we determined the TMIP (Nematimoez and Thomas 2022) of the relative angles using the upper and lower peak values of the first derivative for lifting and lowering, respectively (Figure 1).

Categorisation of spinal movement patterns

To determine the temporal interaction among the eleven spinal segments for each lifting and lowering trial, the TMIP for each step of segmentation was assigned to one of the following three categories: SIM (no change in TMIP), T-D (upper segment causes a decrease in TMIP), and B-U (upper segment causes an increase in TMIP) (Tables 1 and 2).

Finally, the frequency of each pattern was calculated for each trial (Figure 2). This pattern frequency (PF) as a quantity of spinal movement pattern (i.e. T-D, B-U, SIM) was considered for different spinal regions (i.e. whole spine, thoracic spine and lumbar spine) in four lifting techniques conditions: 1) freestyle technique (FST) (Eq. 2.1), 2) squat technique (SQT) (Eq. 2.2), and 3) stoop technique (STT) (Eq. 2.3), 4) regardless of techniques (ALT) (Eq. 2.4) based on the total frequency of all related trials.

$$FST = \begin{cases} WholeSpine_Freestyle = \sum_5^1 Trials_{WholeSpine_Freestyle} \\ ThoracicSpine_Freestyle = \sum_5^1 Trials_{ThoracicSpine_Freestyle} \\ LumbarSpine_Freestyle = \sum_5^1 Trials_{LumbarSpine_Freestyle} \end{cases} \tag{2.1}$$

$$SQT = \begin{cases} WholeSpine_Squat = \sum_5^1 Trials_{WholeSpine_Squat} \\ ThoracicSpine_Squat = \sum_5^1 Trials_{ThoracicSpine_Squat} \\ LumbarSpine_Squat = \sum_5^1 Trials_{LumbarSpine_Squat} \end{cases} \tag{2.2}$$

$$STT = \begin{cases} WholeSpine_Stoop = \sum_5^1 Trials_{WholeSpine_Stoop} \\ ThoracicSpine_Stoop = \sum_5^1 Trials_{ThoracicSpine_Stoop} \\ LumbarSpine_Stoop = \sum_5^1 Trials_{LumbarSpine_Stoop} \end{cases} \tag{2.3}$$

$$ALT = \begin{cases} WholeSpine = WholeSpine_Freestyle + WholeSpine_Squat + WholeSpine_Stoop \\ ThoracicSpine = ThoracicSpine_Freestyle + ThoracicSpine_Squat + ThoracicSpine_Stoop \\ LumbarSpine = LumbarSpine_Freestyle + LumbarSpine_Squat + LumbarSpine_Stoop \end{cases} \tag{2.4}$$

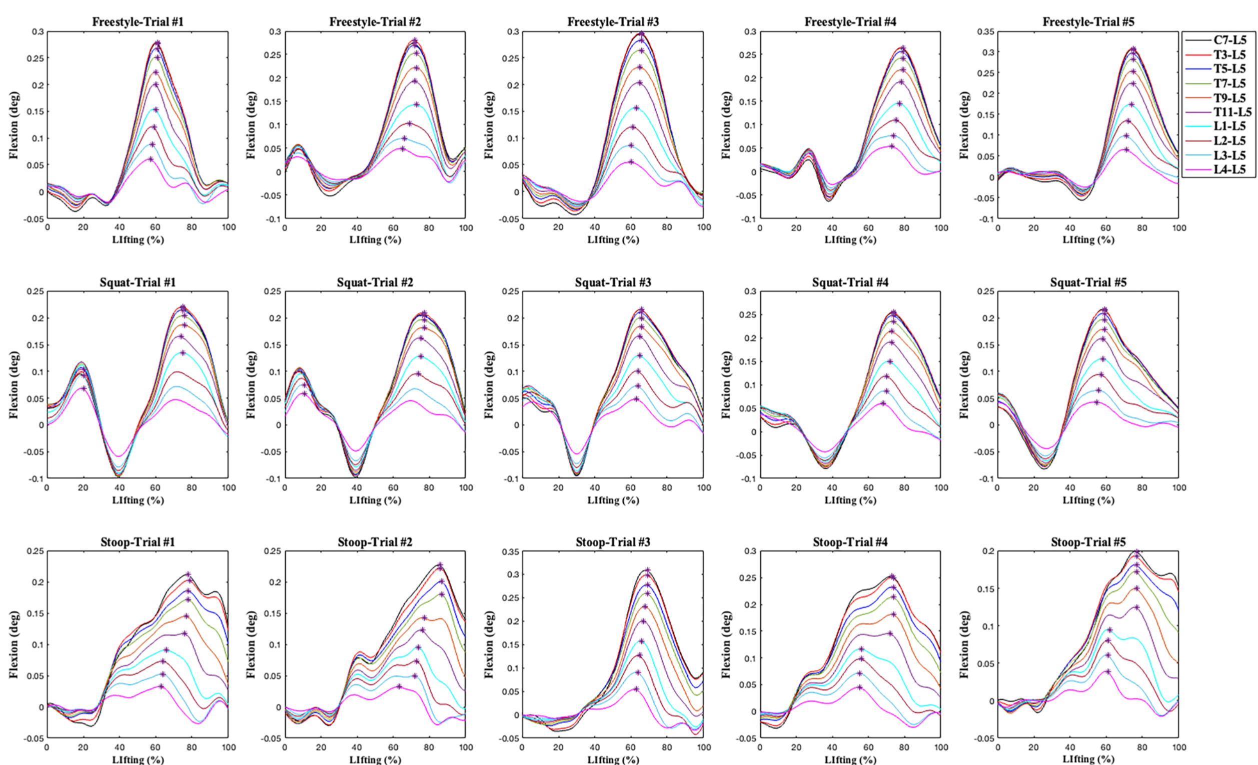

Figure 1. Example of the first derivatives of relative angles and timing of the main inflection points (TMIP) for one participant during object lifting with a freestyle, squat and stoop techniques.

Table 1. Example of pattern frequency procedure for one lifting trial.

N	Segment	Lifting TMIP (%)	Pattern
1	C7-L5	79	-
2	T3-L5	79	'SIM'
3	T5-L5	79	'SIM'
4	T7-L5	79	'SIM'
5	T9-L5	79	'SIM'
6	T11-L5	78	'B-U'
7	L1-L5	77	'B-U'
8	L2-L5	75	'B-U'
9	L3-L5	74	'B-U'
10	L4-L5	73	'B-U'
Pattern frequency for a trial			'T-D'=0, 'B-U'=5, 'SIM'=4

C7 (7th cervical vertebra), T3 (3th thoracic vertebra), T5 (5th thoracic vertebra), T7 (7th thoracic vertebra), T9 (9th thoracic vertebra), T11 (11th thoracic vertebra), L1 (1th lumbar vertebra), L2 (2th lumbar vertebra), L3 (3th lumbar vertebra), L4 (4th lumbar vertebra), L5 (5th lumbar vertebra), TMIP (timing of the main inflection points), SIM (simultaneously), T-D (top-down), B-U (bottom-up).

Statistical analyses

Multiple linear regression analysis was employed to assess the connections between independent variables (gender, with female coded as 1 and male as 2, mass, and height) and PF (Uyanık and Güler 2013). Standardised beta coefficients were utilised to present

Table 2. Example of pattern frequencies for a participant (#11) during lifting.

			Freestyle					Squat					Stoop				
		Paired pattern	#1	#2	#3	#4	#5	#1	#2	#3	#4	#5	#1	#2	#3	#4	#5
Whole Spine	**Thoracic**	C7-L5 & T3-L5	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'	'T-D'	'SIM'	'SIM'	'SIM'	'T-D'	'SIM'	'SIM'	'T-D'	'SIM'
		T3-L5 & T5-L5	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'	'B-U'	'T-D'	'SIM'	'SIM'	'SIM'
		T5-L5 & T7-L5	'SIM'	'T-D'	'SIM'	'SIM'	'SIM'	'T-D'	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'
		T7-L5 & T9-L5	'B-U'	'SIM'	'B-U'	'SIM'	'SIM'	'SIM'	'SIM'	'SIM'	'B-U'	'SIM'	'B-U'	'B-U'	'B-U'	'SIM'	'SIM'
		T9-L5 & T11-L5	'SIM'	'B-U'	'SIM'	'B-U'	'SIM'	'B-U'	'B-U'	'B-U'	'SIM'	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'	'SIM'
	Lumbar	T11-L5 & L1-L5	'SIM'	'T-D'	'B-U'	'B-U'	'B-U'	'T-D'	'SIM'	'SIM'	'B-U'	'SIM'	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'
		L1-L5 & L2-L5	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'	'SIM'	'B-U'
		L2-L5 & L3-L5	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'	'SIM'	'B-U'	'SIM'	'SIM'	'B-U'	'SIM'	'B-U'	'B-U'	'B-U'	'SIM'
		L3-L5 & L4-L5	'B-U'	'B-U'	'SIM'	'B-U'	'SIM'	'SIM'	'SIM'	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'	'B-U'	'SIM'	'SIM'
Trial frequency		top-down ('T-D')	0	2	0	0	0	2	1	0	0	0	1	1	0	1	0
		bottom-up ('B-U')	4	4	4	5	3	2	3	3	4	4	6	6	6	3	2
		simultaneously ('SIM')	5	3	5	4	6	5	5	6	5	5	2	2	3	5	7
Style frequency		top-down ('T-D')			2					3					3		
		bottom-up ('B-U')			20					16					23		
		simultaneously ('SIM')			23					26					19		
Total frequency		top-down ('T-D')								8							
		bottom-up ('B-U')								59							
		simultaneously ('SIM')								68							

C7 (7th cervical vertebra), T3 (3th thoracic vertebra), T5 (5th thoracic vertebra), T7 (7th thoracic vertebra), T9 (9th thoracic vertebra), T11 (11th thoracic vertebra), L1 (1th lumbar vertebra), L2 (2th lumbar vertebra), L3 (3th lumbar vertebra), L4 (4th lumbar vertebra), L5 (5th lumbar vertebra), SIM (simultaneously), T-D (top-down), B-U (bottom-up).

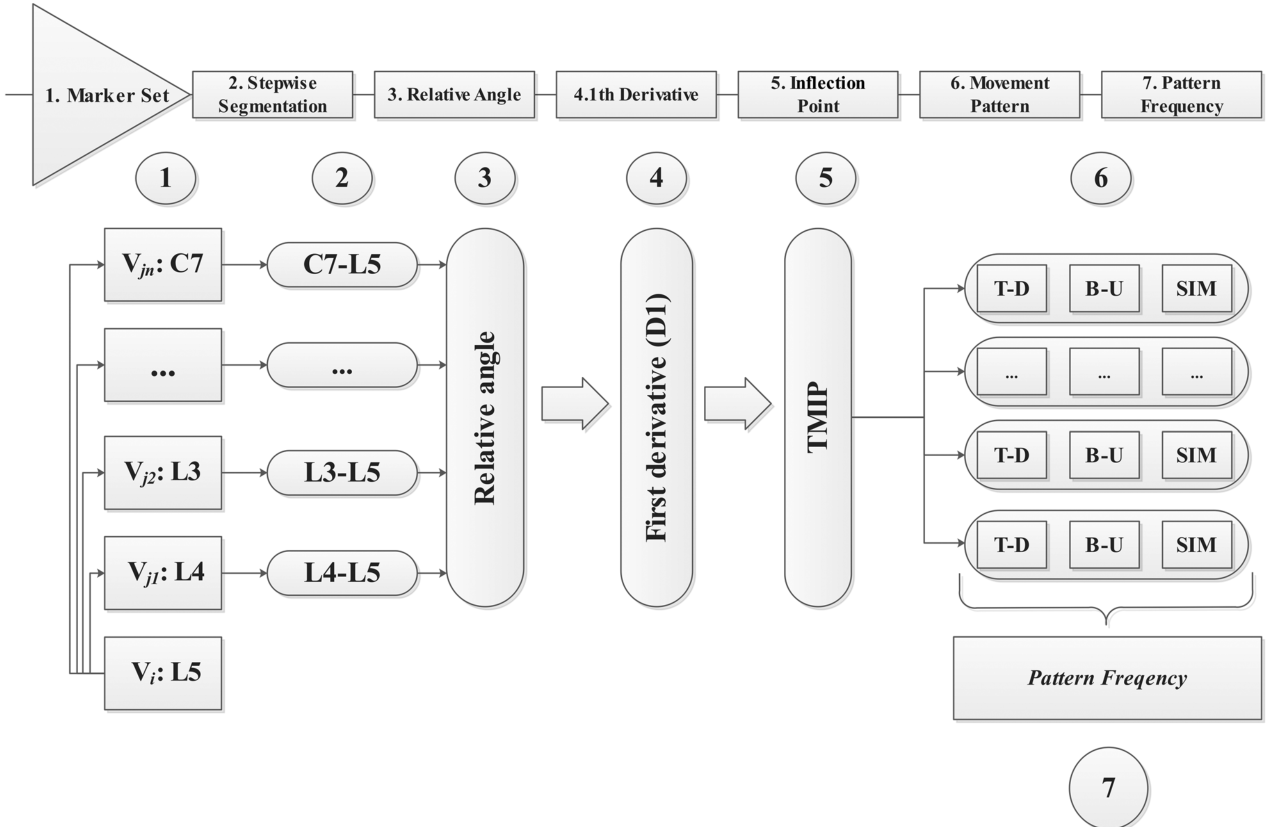

Figure 2. Algorithm for determining pattern frequencies (whole spine, thoracic, and lumbar) for one trial in 7 stages regardless of technique. 1-7: stages for gain pattern frequency; V: level of the spine; i: the main level for stepwise segmentation; j: a level that make segment in each step with level i; n: number of levels for stepwise segmentation; TMIP: timing of the main inflection points; T-D: top-down; B-U: bottom-up; SIM: simultaneous.

these relationships (Eq. 2.5), facilitating comparison between independent variables with distinct metrics (Lafage et al. 2017, Kasch et al. 2022).

$$y = \beta_0 + \beta_1 x_1 + \& + \beta_n x_n + \varepsilon \quad (2.5)$$

Where the y is a dependent variable; X_i is an independent variable (predictor); β_i is a parameter that determine the coincidence for association between y and X_i; ε is an error (Uyanık and Güler 2013).

The variables were analysed using the 'enter' method in SPSS 26 (SPSS Inc., Chicago, IL). The variance inflation factor (VIF) and tolerance (TO) were used to quantify collinearity, with general acceptance established at VIF < 10 and TO > 0.1 cut-offs, respectively (Dormann et al. 2013).

To investigate the potential of PF's to discriminate individual participant characteristics, we used k-means clustering, which is an unsupervised machine learning algorithm that clusters the data based on the mean data point distances and the cluster centroids (Sarker 2021). Linear regression was performed using SPSS 26 (SPSS Inc. Chicago, IL), while k-means clustering was performed using MATLAB.

Results

The collinearity test results showed VIF values below 2.3 and tolerance values above 0.43 for all variables (gender: VIF 1.76, tolerance 0.56; mass: VIF 2.25, tolerance 0.44; height: VIF 2.10, tolerance 0.47).

Whole spine PF's

Table 3 shows the relationships of the whole spine PF's with gender and anthropometrics. For lifting, gender (female=1 and male=2) contributed to the B-U pattern in two conditions: ALT (β=–0.448, p=0.041) and STT (β=–0.612, p=0.002). Conversely, it was associated to the SIM pattern in the STT condition (β=0.425, p=0.031). Mass did not show any contribution to whole spine conditions during this phase of movement. Height was related to the T-D (β=–0.546, p=0.044), B-U (β=–0.422, p=0.041), and SIM (β=0.633, p=0.004) patterns in STT conditions.

During lowering, the contribution of height in B-U pattern was obvious in all four conditions: ALT (β=–0.675, p=0.011), FST (β=–0.645, p=0.017), SQT (β=–0.540, p=0.046), and STT (β=–0.552, p=0.040). The height also contributed to the SIM pattern in two conditions: ALT (β=0.677, p=0.009), SQT (β=0.697, p=0.009). Finally, this variable related to a T-D pattern in the SQT condition (β=–0.581, p=0.035).

Thoracic spine PF's

Table 4 shows the gender and anthropometrics contributions in thoracic PF's. For lifting, gender did not demonstrate any significant contribution to thoracic

Table 3. The whole-spine pattern frequency's association with gender and anthropometrics.

		Lifting			Lowering		
		Gender	Mass	Height	Gender	Mass	Height
WholeSpine T-D	Beta	0.214	–0.146	–0.142	–0.081	0.094	–0.379
	Sig.	0.409	0.617	0.615	0.740	0.733	0.164
WholeSpine B-U	Beta	**–0.448**	0.138	–0.328	–0.026	0.345	**–0.675**
	Sig.	**0.041**	0.564	0.162	0.909	0.185	**0.011**
WholeSpine SIM	Beta	0.258	–0.036	0.352	0.062	–0.293	**0.677**
	Sig.	0.257	0.888	0.160	0.779	0.246	**0.009**
WholeSpine_Freestyle T-D	Beta	0.080	–0.209	0.037	–0.063	–0.147	–0.012
	Sig.	0.758	0.480	0.897	0.807	0.614	0.966
WholeSpine_Freestyle B-U	Beta	–0.356	–0.046	–0.056	0.079	0.304	**–0.645**
	Sig.	0.144	0.864	0.831	0.737	0.257	**0.017**
WholeSpine_Freestyle SIM	Beta	0.197	0.195	0.012	–0.009	–0.102	0.439
	Sig.	0.425	0.483	0.964	0.970	0.713	0.109
WholeSpine_Squat T-D	Beta	0.130	–0.224	0.017	0.193	0.266	**–0.581**
	Sig.	0.618	0.448	0.953	0.427	0.334	**0.035**
WholeSpine_Squat B-U	Beta	–0.106	–0.436	0.666	–0.031	0.235	**–0.540**
	Sig.	–0.319	–1.207	0.238	0.898	0.386	**0.046**
WholeSpine_Squat SIM	Beta	0.009	0.104	0.240	–0.089	–0.310	**0.697**
	Sig.	0.972	0.712	0.380	0.696	0.235	**0.009**
WholeSpine_Stoop T-D	Beta	0.356	0.238	**–0.546**	–0.376	0.034	–0.104
	Sig.	0.145	0.382	**0.044**	0.123	0.899	0.689
WholeSpine_Stoop B-U	Beta	**–0.612**	0.320	**–0.422**	–0.125	0.384	**–0.552**
	Sig.	**0.002**	0.127	**0.041**	0.598	0.158	**0.040**
WholeSpine_Stoop SIM	Beta	**0.425**	–0.404	**0.633**	0.330	–0.263	0.415
	Sig.	**0.031**	0.066	**0.004**	0.156	0.312	0.104

SIM (simultaneously), T-D (top-down), B-U (bottom-up), Sig. (significant), Beta (Standardised beta coefficient), WholeSpine: is pattern frequency for fifteen trials of all techniques and whole spine; WholeSpine_Free style: is pattern frequency for five trials of Free style technique and all spine segments; WholeSpine_Squat: is pattern frequency for five trials of squat technique and all spine segments; WholeSpine_Stoop: is pattern frequency for five trials of stoop technique and all spine segments; Bold values indicate statistical significance $p < 0.05$.

Table 4. The thoracic spine pattern frequency's associations with gender and anthropometrics.

		Lifting			Lowering		
		Gender	Mass	Height	Gender	Mass	Height
ThoracicSpine T-D	Beta	−0.073	0.047	−0.224	−0.386	**0.590**	−0.378
	Sig.	0.776	0.871	0.426	0.107	**0.032**	0.146
ThoracicSpine B-U	Beta	−0.406	0.266	−0.429	0.086	0.110	**−0.558**
	Sig.	0.068	0.280	0.076	0.715	0.681	**0.038**
ThoracicSpine SIM	Beta	0.329	−0.215	0.442	0.151	−0.392	**0.578**
	Sig.	0.143	0.391	0.075	0.517	0.143	**0.030**
Thoracic_Freestyle T-D	Beta	0.008	−0.106	0.014	−0.334	0.431	−0.188
	Sig.	0.976	0.720	0.960	0.185	0.132	0.489
Thoracic_Freestyle B-U	Beta	−0.408	0.409	−0.134	−0.058	0.311	−0.496
	Sig.	0.105	0.149	0.618	0.811	0.265	0.071
Thoracic_Freestyle SIM	Beta	0.235	−0.165	0.069	0.252	−0.462	0.410
	Sig.	0.365	0.572	0.807	0.302	0.100	0.129
Thoracic_Squat T-D	Beta	−0.208	0.056	−0.007	−0.081	0.351	−0.363
	Sig.	0.424	0.849	0.980	0.750	0.224	0.195
Thoracic_Squat B-U	Beta	−0.154	−0.184	−0.082	0.038	−0.039	−0.319
	Sig.	0.531	0.507	0.760	0.878	0.891	0.246
Thoracic_Squat SIM	Beta	0.249	0.118	0.071	0.022	−0.176	0.400
	Sig.	0.310	0.669	0.789	0.929	0.535	0.151
Thoracic_Stoop T-D	Beta	0.003	0.160	−0.453	−0.352	0.290	−0.080
	Sig.	0.991	0.565	0.100	0.169	0.312	0.772
Thoracic_Stoop B-U	Beta	−0.333	0.374	**−0.647**	0.237	0.057	**−0.537**
	Sig.	0.103	0.105	**0.006**	0.327	0.834	**0.048**
Thoracic_Stoop SIM	Beta	0.230	−0.359	**0.731**	0.080	−0.217	0.373
	Sig.	0.247	0.114	**0.002**	0.751	0.446	0.180

SIM (simultaneously), T-D (top-down), B-U (bottom-up), Sig. (significant), Beta (Standardised beta coefficient); ThoracicSpine: is pattern frequency for fifteen trials of all techniques and thoracic segments; Thoracic_Free style: is pattern frequency for five trials of Free style technique and thoracic segments; Thoracic_Squat: is pattern frequency for five trials of squat technique and thoracic segments; Thoracic_Stoop: is pattern frequency for five trials of stoop technique and thoracic segments; Bold values indicate statistical significance $p < 0.05$.

PF's. Height was associated to the B-U and SIM patterns in a condition: STT (β=−0.647, p=0.006 and β=0.731, p=0.002, respectively).

During lowering, height contributed to the B-U pattern in the ALT (β=−0.558, p=0.038) and STT (β=−0.537, p=0.048) conditions. This variable also related to the SIM pattern in the ALT (β=0.578, p=0.030) condition, wherein the thoracic segment was considered. In this phase, the mass contributed to the T-D pattern in the ALT condition (β=0.590, p=0.032).

Lumbar spine PF's

Table 5 shows the results of the linear regression analysis determining the contributions of gender and anthropometrics in lumbar PF's. During lifting, gender was associated to the B-U and SIM patterns in the STT condition (β=−0.638, p=0.004 and β=0.461, p=0.045, respectively).

For lowering, height contributed to the B-U pattern in three conditions: ALT (β=−0.594, p=0.027), FTT (β=−0.546, p=0.048), and SQT (β=−0.587, p=0.029). In addition, it was related to the SIM pattern in the ALT (β=−0.639, p=0.014) and SQT conditions (β=0.841, p=0.001), as well as to the T-D pattern in the SQT condition (β=−0.603, p=0.024).

PF's clustering

As Figure 3 shows, regardless of lifting technique, the B-U pattern of the thoracic spine (ThoracicSpine B-U) was the best gender discriminating variable. Eighty percent of females (n=8) versus 15% of males (n=3) grouped in a cluster. Although in some variables such as Spine-Stoop SIM, 90% of females were in a cluster, the number of males in this cluster cannot be ignored (n=8, 40%).

Discussion

This study aimed to explore the relationships between individual participant characteristics and PF's during the lifting and lowering of a box using various techniques. Overall, patterns were more consistently linked with individual participant characteristics during lifting phases compared to lowering phases. In stoop lifting, females and shorter participants predominantly exhibited a bottom-up pattern, while males and taller participants tended to demonstrate a simultaneous pattern. Notably, the correlation between gender and the bottom-up pattern was more pronounced for the lumbar spine than for the thoracic and whole spines. Conversely, during lowering, regardless of spine region or technique, patterns were primarily associated with the height of participants rather than gender and mass. Additionally, cluster analysis indicated that thoracic spine bottom-up movements better distinguished between males and females compared to any other PF variable.

Table 5. The lumbar spine pattern frequency's associations with gender and anthropometrics.

		Lifting			Lowering		
		Gender	Mass	Height	Gender	Mass	Height
LumbarSpine T-D	Beta	0.347	−0.235	−0.047	0.148	−0.264	−0.237
	Sig.	0.178	0.415	0.866	0.546	0.342	0.375
LumbarSpine B-U	Beta	−0.417	0.063	−0.244	−0.099	0.429	**−0.594**
	Sig.	0.066	0.800	0.314	0.674	0.114	**0.027**
LumbarSpine SIM	Beta	0.179	0.077	0.248	−0.024	−0.157	**0.639**
	Sig.	0.451	0.772	0.341	0.913	0.535	**0.014**
Lumbar_Freestyle T-D	Beta	0.116	−0.249	0.047	0.141	−0.456	0.107
	Sig.	0.656	0.399	0.869	0.573	0.113	0.694
Lumbar_Freestyle B-U	Beta	−0.255	−0.229	−0.010	0.146	0.205	**−0.546**
	Sig.	0.285	0.394	0.969	0.550	0.457	**0.048**
Lumbar_Freestyle SIM	Beta	0.135	0.381	−0.026	−0.225	0.236	0.308
	Sig.	0.565	0.157	0.920	0.356	0.390	0.250
Lumbar_Squat T-D	Beta	0.275	−0.308	0.025	0.407	0.085	**−0.603**
	Sig.	0.286	0.290	0.930	0.089	0.748	**0.024**
Lumbar_Squat B-U	Beta	−0.057	0.173	−0.434	−0.084	0.414	**−0.587**
	Sig.	0.817	0.533	0.113	0.723	0.129	**0.029**
Lumbar_Squat SIM	Beta	−0.144	0.079	0.309	−0.192	−0.377	**0.841**
	Sig.	0.567	0.781	0.265	0.371	0.126	**0.001**
Lumbar_Stoop T-D	Beta	0.418	0.134	−0.229	−0.232	−0.162	−0.077
	Sig.	0.092	0.625	0.387	0.338	0.551	0.769
Lumbar_Stoop B-U	Beta	**−0.638**	0.228	−0.219	−0.295	0.401	−0.284
	Sig.	**0.004**	0.319	0.322	0.238	0.159	0.298
Lumbar_Stoop SIM	Beta	**0.461**	−0.322	0.365	0.421	−0.202	0.291
	Sig.	**0.045**	0.203	0.138	0.072	0.433	0.246

SIM (simultaneously), T-D (top-down), B-U (bottom-up), Sig. (significant), Beta (Standardised beta coefficient); LumbarSpine: is pattern frequency for fifteen trials of all technique and lumbar segments; Lumbar_Free style: is pattern frequency for five trials of Free style technique and lumbar segments; Lumbar_Squat: is pattern frequency for five trials of squat technique and lumbar segments; Lumbar_Stoop: is pattern frequency for five trials of stoop technique and lumbar segments; Bold values indicate statistical significance $p < 0.05$.

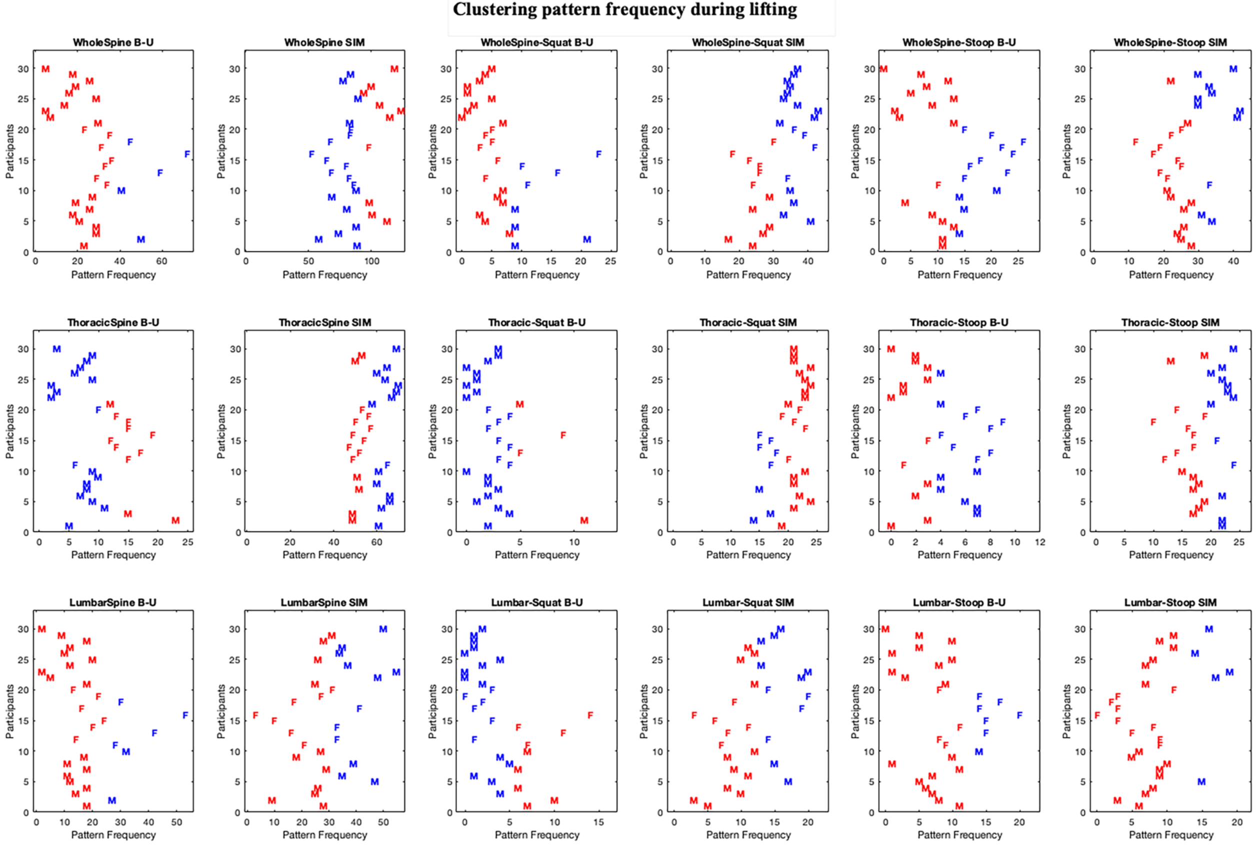

Figure 3. Scatter of clustering the pattern frequencies (bottom-up and simultaneous) during lifting using the k-means algorithm (k = 2). The blue and red colouring discriminates the two identified data clusters. ***B-U***: bottom-up; ***SIM***: simultaneous; ***M:*** Male; ***F:*** female.

Individual participant characteristics and PF's

Using multiple linear regression analysis with gender, height, and mass as predictor variables may raise concerns about the relationships among these predictors. To address this issue, the current study assessed collinearity by the IVF and TO variables (Marill 2004, Dormann et al. 2013). The results of the analysis showed that there was no significant concern regarding the association between any of the predictors and PFs. While there is some overlap among these variables, it is still valuable to consider them. In other words, these predictors offer the best opportunity for forecasting PFs in relation to the complexity of the spine as a multisegmented system.

Some studies have considered movement patterns in lower extremity joints (i.e. knee, hip, and pelvis) and back (lumbar spine)(Plamondon et al. 2014, Yehoyakim et al. 2016, Plamondon et al. 2017). However, the detailed spinal movement pattern has not been investigated. Some factors such as muscle strength, load, and work experience have identified as variables that could determine movement patterns. Plamondon and colleagues reported a sequential movement pattern (i.e. bottom-up and not simultaneous) as a strategy to utilise passive tissues for lumbar control and movement by female manual material handlers, a pattern that was observed even in a condition where the load was normalised based on the overall strength of each gender (females/males: 2/3 or 10 kg vs. 15 kg) (Plamondon et al. 2014, Plamondon et al. 2017). Nevertheless, simultaneous knee, hip and back movement patterns are associated with the level of work experience (i.e. manual handling) as exhibited by expert male manual material handlers. Yehoyakim and colleagues demonstrated a relationship between inter-joint coordination and young females' knee and back strength (Yehoyakim et al. 2016). They found that greater strength in the hip and back led to a more synchronised motion pattern. Granata and Sanford underlined a simultaneous pattern for the lumbar and pelvic during lifting a light load (i.e. 0.1 kg) with a lumbar spine contribution that increased nonlinearly for lifting a heavier load (i.e. 10 kg) (Granata and Sanford 2000). In this investigation, participants were both males ($n=13$) and females ($n=5$) with different sample sizes (males > females). In the present study, a simultaneous pattern was also revealed for the spine, specifically in the male participants. It seems that these strategies are not limited to the knee, hip, and back those previous studies reported (Plamondon et al. 2014, Gagnon, Plamondon, and Larivière 2018) but might also occur within different regions of the spine. Therefore, the synchronised pattern is a strategy which is more common in males and experienced manual material handlers. On the other hand, the sequential pattern seems to be more common in females. The k-means cluster analysis, which is an unsupervised machine learning approach, confirmed and highlighted the B-U pattern for the thoracic spine in 80% of female participants, identifying it as the most effective discriminating factor. This finding also supports the potential of PF as an input variable in various machine learning algorithms.

Regarding anthropometric characteristics, height demonstrated notable associations primarily with simultaneous and bottom-up movement patterns, particularly during the lowering phase. It appears that taller individuals exhibited the simultaneous pattern more frequently than other patterns, suggesting that this pattern may offer them optimal performance, particularly in terms of mechanical advantage. Previous research suggests that taller, heavier, and stronger individuals tend to favour the stoop technique, likely due to its demonstrated energy efficiency over other techniques (Burgess-Limerick and Abernethy 1997). In the current study, the relationship between gender and lumbar PF's during stoop lifting revealed that females predominantly employed a bottom-up pattern, also known as 'back lifting', relying more on back muscle strength compared to the squat and semi-squat techniques. Consequently, PF during stoop lifting appears to be more influenced by gender compared to other lifting techniques such as squat lifting.

Practical implication of PF for ergonomic interventions

As stated in the introduction, there are no agreements about safety and imposed loads for different techniques (van Dieen et al. 1999, Khoddam-Khorasani, Arjmand, and Shirazi-Adl 2020, Von Arx et al. 2021). In addition, given that the subjects experience homogeneity and were not manual material handlers or athletes, discussing the advantages and disadvantages of these spinal movement patterns is not in the scope of the present study. Nevertheless, the results could provide an insight into the design of tailored exercises that might help individuals to prepare for daily living, sports and work-related activities. In the following, we therefore suggest some factors to consider for training, which could contribute to the prevention of injuries and pain.

Considering B-U and SIM of spinal movement patterns from two points of view may be helpful for designing an exercise program. First, how is the spinal stability provided by the subsystems for these patterns (Panjabi 1992). As aforementioned, some researchers believe that sequential movement pattern is related to

passive subsystem employment. For a more in-depth evaluation of these patterns, we may require a review of some anatomical and mechanical properties of the spine, specifically the lumbar region. Lower levels of the spine (i.e. lumbar) are surrounded by many passive and active structures that could provide mechanical advantages. About eight long fascicles of the iliocostalis lumborum pars thoracic and longissimus thoracic pars thoracic from the thorax attach to the sacrum and ilium directly or through spinae aponeurosis (Macintosh and Bogduk 1991). Additionally, four fascicles of iliocostalis lumborum pars lumborum and five fascicles of longissimus thoracic pars lumborum are attached to the iliac crest. However, some fascicles of longissimus thoracic pars thoracic are not passed throughout the whole lumbar spine and are attached serially to the L1-S4 (Macintosh and Bogduk 1991). Multifidus muscles also have purposeful architecture (i.e. high cross-sectional area and short fibre length) for lumbar stability and they seem designed to be stronger when the trunk is flexed (Ward et al. 2009). The thoracolumbar fascia consisted of two or three layers that join together in the lower lumbar and attach to the posterior superior iliac spine (Willard et al. 2012). Therefore, the spinal movement initiated from lower levels may be led to include more muscles to move the trunk while some regional muscles may be reserved to continue the motion and their stability partly donated by the passive subsystem. On the other hand, SIM pattern may require an active subsystem and sophisticated motor control strategies. For this pattern, neuromuscular coordination and some level of conditioning would be necessary due to the multi-segmental structure and morphological complexity of erector spinae muscle groups (Oxland 2016).

For individuals with a B-U pattern, the program may focus on the exercise that involves full spine range of motion with sequential patterns to involve Multifidus and passive subsystems. Many studies reported the benefits of different training modes on Multifidus muscles. For example, it was reported that 10 weeks of dynamic isolated resistance-training program in 16 chronic non-specific low back pain (CNSLBP) patients had functional beneficial effects. This training mode prescribes a slow and full spinal range of motion and restricted lower extremities and hip movements (Willemink et al. 2012). Berglund et al., observed the positive effects of the two months of motor control or deadlift exercises on Multifidus thickness regardless of training loads on 65 subjects with nociceptive mechanical LBP. Motor control exercises are carried out statically and dynamically without external loads with concentration on control and timing of the movements in the lumbar spine. The deadlift included sessional progressive lifting up and putting down the barbell from the floor level (Berglund et al. 2017).

It seems the exercises could be effective for people with SIM patterns which require more neuromuscular coordination characterised by the regular range of motion and speed (Steele, Bruce-Low, and Smith 2015). Indeed, this pattern requires precise timing and control of complex back muscles with sophisticated motor control strategies. As previously mentioned, deadlift is effective for improving Multifidus and involving erector spinae (Nijem et al. 2016); it is partly similar to common activity in working environments but in planned repetition, load, and breaking rest as a procedure of the training programs. Any exercise programs accordingly may be superior to work experiences (Beach et al. 2014).

Strength and limitation of study

For the first time, multi-segmental interactions and spinal movement patterns were categorised and comprehensively evaluated with respect to gender, body anthropometry and lifting technique. A strength of this method would be modifying within and between-subjects high level of variability. In preliminary analyses, there were 300 and 266 temporal interaction patterns (for 450 trials) among spinal segments for lifting and lowering, respectively.

This study has some limitations that should be addressed. Firstly, soft tissue artefacts might have influenced the accurate determination of the vertebral angles. However, since our focus was on the spinal movement pattern of the inter-segmental motions, this had most likely no or an only minor impact on the main outcomes of this study. Secondly, the unequal distribution of males (n = 20) and females (n = 10) might have reduced the strength of the correlations between gender and PF's. Nevertheless, gender still demonstrated potential as a pattern predictor even within unequal participant groups. Thirdly, although the used method acceptably reduced the variability of the data, there are some unsolved levels of variability in the data, which is why the results should be interpreted with caution. Furthermore, some aspects of the experiment, e.g. mass, size, and shape of the box as well as lifting velocity, might limit the generalisation our results. Hence, it cannot be excluded that different lifting conditions result in different spinal movement patterns and different associations with gender and body anthropometry. Finally, we did not account for inter-subject differences in maximum range of motion of the individual spinal segments. It might therefore

be that some of the motion patterns might be influenced by limited flexibility.

As recommendations for future studies, it would be necessary to find the relationship between PF's and segmental loads. Furthermore, investigating different population groups could help to better understand the PF and be comparable with findings of the current study; these populations could consist of LBP patients (pathological conditions), athletes (trained individuals) and experienced manual material handlers. Based on the results of the cluster analysis and the measurement options provided by PF concerning the combination of segments, techniques, and phases, future studies may find it beneficial to use this information as input for machine learning algorithms to explore additional characteristics of the populations.

To conclude, gender, height, technique and their combinations could influence spinal movement pattern. Females showed more sequential pattern, while males adopted more synchronised pattern. PF was introduced as a quantification variable for categorisation and could be used for designing more subject-specific exercise programs in ergonomic and clinical settings. Additionally, this variable offers the possibility of utilising unsupervised machine learning algorithms to investigate individual characteristics.

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