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The mental representation of the human gait in patients with severe knee osteoarthrosis: a clinical study to aid understanding of impairment and disability

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Abstract

Objective: Objectives were (1) to explore differences in gait-specific long-term memory structures and gait performance between knee osteoarthrosis patients and healthy subjects and (2) to identify the extent to which the gait-specific mental representation is associated with gait performance.

Design: Cross-sectional study.

Subjects: In total, 18 knee osteoarthrosis patients and 18 control subjects.

Methods: Spatio-temporal (gait speed, step length) and temporophasic (stance time, swing time, single support time, total double support time) gait parameters and gait variability were measured with an electronic walkway (OptoGait). The mental representation was assessed using the structural dimensional analysis of mental representations (SDA-M).

Results: (1) Patients showed significantly longer stance times ($P < 0.002$) and total double support times, shorter swing times and single support times, a decreased gait speed (P-values < 0.001) and structural differences in the gait-specific mental representation as compared with the healthy controls. (2) Correlation analyses revealed the mental representation of the human gait to be associated with actual gait performance in osteoarthrosis patients. Double support times were positively associated with the structural quality of the mental representation and step length variability was positively associated with the number of sequencing errors in the representation.

Conclusion: The gait-specific mental representation and actual gait performance differ between patients with severe knee osteoarthrosis and healthy controls, and both are linked to one another. This finding suggests that musculoskeletal disorders can lead to changes in the mental representation of the gait, and as such the SDA-M could provide useful information to improve the rehabilitation following osteoarthrosis.

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Introduction

Osteoarthrosis is one of the most common joint diseases, including a destruction of joint structures.[1,2] Patients with severe knee osteoarthrosis are affected by inflammation, swelling and pain resulting, in particular, in an inability to fully activate the quadriceps muscle, a process known as arthrogenic muscle inhibition,[3] a feedback mechanism found to protect the joint structures.[4] As a consequence, patients with severe knee osteoarthrosis suffer from muscle weakness,[5–8] use compensatory movement patterns to minimize or avoid postures associated with pain[9,10] and are limited in a wide range of activities of daily living, which in sum affect their quality of life.[11] With regard to biomechanical and functional characteristics, it has been shown that patients with severe knee osteoarthrosis have a reduced knee joint range of motion,[12] decreased stride length,[13] lower gait speed,[14] longer double support times,[15] increased knee flexion at heel strike,[16] reduced knee flexion during the stance phase,[17] lower external knee flexion moments during early stance[18] and lower external knee extension moments in terminal stance.[19]

Considering previous work,[20] such disease-related gait abnormalities and painful events as described for knee osteoarthrosis may also affect (and then be affected by changes in) the neurologically generated gait pattern as represented in mind (i.e. long-term memory). It is already known that mental representations play a decisive role in the control and organization of motor actions which are denoted by well-integrated networks of mental representation structures.[21] Based on the literature, human motor actions are stored in major representation units,[21,22] similar to knowledge taxonomies suggested for object representation.[23] Mental representations are linked to perceptual effects and correspond to the functional structures of the respective movement.[22,24,25] Land et al.[25] have shown a relationship between the mental representation and the kinematic structure of a certain movement for a variety of movement skills. A common psychometric tool to assess long-term memory structures of motor actions is the structural dimensional analysis of mental representations (SDA-M).[21,26] Besides its traditional application in the field of sports,[25,27] the SDA-M has also been applied to basic research, especially for the examination of the mental representation in stroke patients during drinking out of a cup,[28] or in subjects with gait abnormalities.[20] For the human gait, Stöckel et al. reported a link between the gait-specific mental representation structure and actual gait performance. The authors compared gait parameters at a comfortable gait speed (assessed with OptoGait) and the gait-specific mental representation (assessed with SDA-M) between slow and fast walking young adults. Based on the finding that slow-walking adults more often had a history of lower leg injuries, they hypothesized that musculoskeletal injuries/disorders of the lower extremities lead to changes in action-related knowledge of the human gait in long-term memory.[20]

In that regard, the aims of this study were (1) to explore differences between gait-specific long-term memory structures (cognitive level) and actual gait performance (motor level) among patients with severe knee osteoarthrosis and healthy age-homogeneous adults and (2) to study the relation between the gait-specific mental representation and actual gait performance in patients with severe knee osteoarthrosis. Based on previous work,[20] we hypothesized that severe

knee osteoarthrosis leads to differences in gait characteristics and in gait-specific long-term memory structures compared to healthy age-matched controls.

Materials and methods

Ethics statement

This cross-sectional study was carried out in the Department of Orthopaedics at the University Medicine Rostock. The study was approved by the Ethical Review Committee of the University of Rostock (A 2013-0150).

Participants

In all, 18 patients with severe knee osteoarthrosis scheduled for right-sided primary total knee arthroplasty (patient group) and 18 control subjects with no history of neurological and musculoskeletal disorders/injuries (control group) volunteered for this study. Patients were identified as being suitable for inclusion in the study if they were aged between 50 and 80 years and had a body mass index of less than 40. Patients with a total knee endoprosthesis on the contralateral side or a total hip endoprosthesis were excluded if the surgery was performed within the preceding year.[29] Furthermore, additional exclusion criteria were defined: musculoskeletal and neurological disorders, metabolic bone disease, an operation planned within the next 12 months and pain or functional restrictions which would prevent patients from taking part in physical examinations. Before participation, written informed consent was obtained from all participants.

Experimental design and procedures

All participants underwent testing of actual gait performance and gait-specific long-term memory structures (SDA-M) within a single 1-hour session. In addition, demographic characteristics (e.g. age, gender, height and weight), physical activity (in hours per week) and knee pain (visual analogue scale[30]) were recorded for all participants. Patients with severe knee osteoarthrosis were examined one day before total knee arthroplasty. The data were collected by the same investigator.

Gait performance

Gait performance was assessed with the OptoGait floor-based photocell system (Microgate, Bolzano, Italy). The measurement was carried out in a quiet room, with no auditory or visual interference. The electronic walkway consisted of six transmitting and six receiving bars which were placed parallel to each other (distance between the bars: 1 m). During the examination, subjects wore their own footwear; participants were asked to wear closed shoes with heel height not exceeding 3 cm.[31] Subjects were instructed to walk along the 6-m walkway at self-selected comfortable speed, starting and finishing each walk 2 m before and after the walkway. Two familiarization and five experimental trials with a rest interval of 1 minute between trials were performed. The data were sampled at 1 kHz and analyzed using the OptoGait software (version 1.8.0.0., Microgate, Bolzano, Italy) and a custom-written Excel spreadsheet (Excel 2010, Microsoft Inc., Seattle, USA). Only the data of the right leg (which corresponds to the affected leg in the patient group) were considered for further analysis. Data were collected from two spatio-temporal (step length and gait speed) and four temporophasic parameters (stance time, swing time, single support time and total double support time as a percentage of the gait cycle). The gait speed was adjusted to height (gait speed/height). Moreover, gait variability as an indicator for the risk of falling, was calculated for step length (coefficient of variation for step length $[CV_{step\ length}] = (\text{standard deviation/mean}) \times 100$).[32] The mean value of each parameter for the five experimental trials was calculated.

All data were checked for normality and homogeneity. Differences between the groups (patient group vs control group) were tested using chi-square test (parameter: sex), unpaired Student's *t*-tests (parameters: age, weight, height, physical activity, number of steps) and separate one-way analyses of covariance adjusted for weight (all gait parameters). The level of statistical significance

was set at $P \leq 0.05$. All data were analyzed using the SPSS statistical package 20.0 (SPSS Inc., Chicago, IL, USA). The effect size and power were calculated with G*Power (version 3.1.4.). The effect size *f* was interpreted using the classification of Cohen:[33] $f = 0.10$ small effect, $f = 0.25$ moderate effect, $f = 0.40$ large effect. The data are presented as mean (standard deviation) or estimated marginal means (estimated standard deviation) in the tables. If appropriate, data are reported as mean difference (MD) and 95% confidence interval (95% CI).

Mental representation of the gait

The mental representation of the human gait was assessed using the SDA-M.[20,27,34] Based on the literature, a gait cycle consists of two main phases—the stance and swing phase—and eight functional periods—initial contact, loading response, mid-stance, terminal stance, pre-swing, initial swing, mid-swing and terminal swing.[10,20] These eight functional periods were specified as basic action concepts (BACs) of the human gait in the splitting procedure of the SDA-M. The right limb was marked in black for the presentation because the right leg was the affected side in all patients in this study.

Pilot data demonstrated that the terminal swing and the initial contact are not clearly distinguishable from each other. Consequently, the last period (the terminal swing, Figure 1) was not used for the splitting procedure.[20] The examination was carried out in a quiet room with no auditory and visual disturbances. The splitting procedure was presented to the participants on a 19-inch monitor. During the splitting procedure, one picture was always located at the top of the screen (as an anchoring picture). Participants were asked to classify the remaining N-1 pictures as similar or dissimilar to the reference picture by pressing left and right navigation keys for "yes" or "'no," respectively. The assignment of pictures depended on whether the presented BACs were closely related to one another within the gait cycle or not. After all the judgements were made for an anchoring picture, another BAC was randomly placed in the anchoring position, and all other BACs were compared to this reference picture. This procedure was repeated until each of the BACs was in the anchoring position. Based on the decisions during the splitting procedure, a Euclidean distance matrix between all BACs was calculated. A hierarchical cluster analysis was then applied to compute the individual mental representation structures of the gait (i.e. dendrograms showing the individual cluster solutions based on Euclidean distances; for more detail regarding SDA-M, see Schack[27] and supplementary material to Stöckel et al.[34]).

For all cluster analyses, a critical value of $d_{crit} = 3.53$, reflecting an alpha level of $\alpha = 0.05$, was used to determine the statistical relevance of links between BACs; with only links below this critical value being considered as statistically relevant (i.e. related to each other). Between-group comparisons of the cluster solutions derived from SDA-M were performed by determining the structural invariance (λ) between the grouped cluster solutions (i.e. mean group dendrograms derived from cluster analysis by summing the individual Z-matrices). According to the literature, an invariance measure of $\lambda < \lambda_{crit} = 0.68$ was used to determine significance at an alpha level of $\alpha = 0.05$.[27] Pearson product–moment correlation coefficients (*r*) were used to examine the relationship between the individual λ-values (quality of the mental representation of the gait) and measures of gait performance (gait speed/height, $CV_{step\ length}$, stance time, swing time, single support time, total double support time). All correlations were controlled for weight due to the proven impact of weight on gait parameters.[35,36] Correlation coefficients between 0.1 and 0.3 were defined as small, between 0.3 and 0.5 as moderate and between 0.5 and 1.0 as strong correlations.[33] The level of significance was established at $P \leq 0.05$. Correlation analyses were performed using SPSS statistical package 20.0.

Results

The patient group and control group differed significantly in weight. No between-group differences

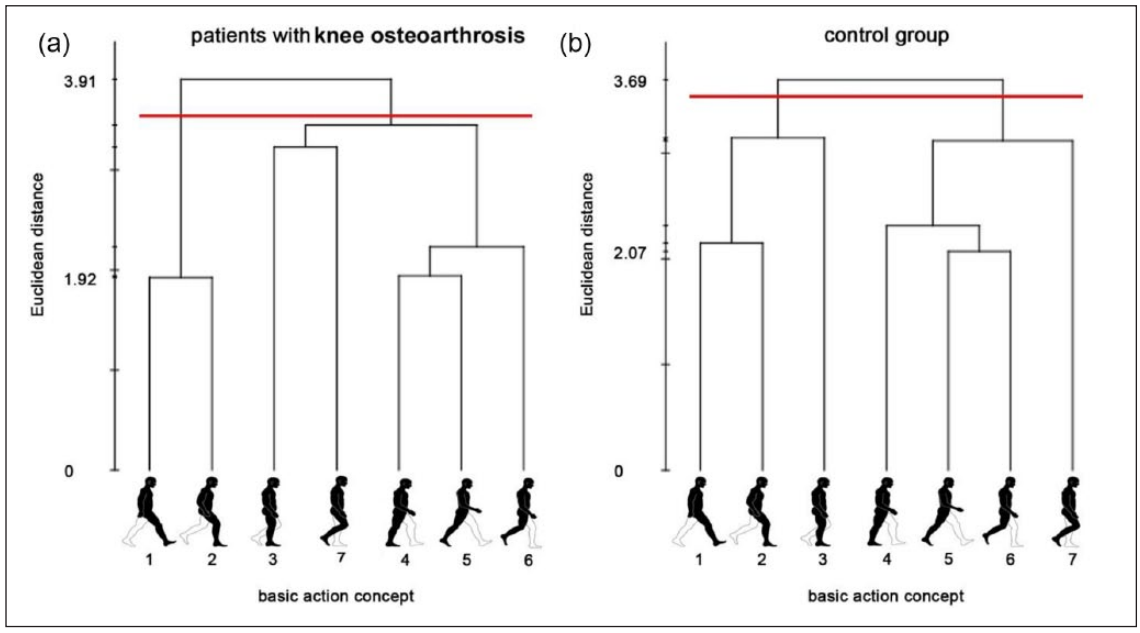

Figure 1. Mean group dendrograms for (a) patients with severe knee osteoarthrosis (patient group) and (b) age-matched healthy controls (control group). The y-axis displays the Euclidean distances (anchoring depth) between basic action concepts (BACs, i.e. the functional periods). The horizontal line indicates the critical Euclidean distance of 3.53, below which links between BACs are considered being statistically significant. The x-axis shows the BACs: (1) initial contact, (2) loading response, (3) mid-stance, (4) terminal stance, (5) pre-swing, (6) initial swing and (7) mid-swing.

were found for all other anthropometric data and physical activity (Table 1).

Spatio-temporal and temporophasic gait parameters

A total number of 18.74 and 16.21 steps were analyzed in the patient group and control group, respectively. Gait speed/height was significantly lower in the patient group compared to the control group (15.48%). Furthermore, the patient group showed a significantly longer stance time (4.98%) and a shorter swing time (8.49%). The single support time was lower in the patient group as compared to the control group (8.68%). In contrast, the total double support time was significantly longer in the patient group than in the control group (29.12%). Spatio-temporal and temporophasic gait parameters and $CV_{step\ length}$ are reported in Table 1.

Mental representation of the gait

Comparison of the mean group dendrograms revealed structural differences in the patient group as compared to the control group. That is, there were distinct clusters for BACs 1–3 (initial contact, loading response, mid-stance) and BACs 4–7 (terminal stance, pre-swing, initial swing, mid-swing) ($d = 3.69$; $P < 0.05$) in the control group (Figure 1(b)) while in the patient group there were two distinct clusters for BACs 1 and 2 (initial contact, loading response) and BACs 3–7 (mid-stance, terminal stance, pre-swing, initial swing, mid-swing; $d = 3.91$; $P < 0.05$) (Figure 1(a)) with BACs 3 (mid-stance) and 7 (mid-swing) not being clustered together with the functional periods appearing right before them in the gait cycle; instead these two BACs were clustered together in the mean group dendrogram of the patient group. However, having a closer look at the individual cluster solutions of the gonarthrosis

Table 1. Demographic and clinical subject characteristics and spatio-temporal and temporophasic gait parameters of knee osteoarthrosis patients and healthy controls.

	Patient group ($n=18$)	Control group ($n=18$)	MD	95% CI	*P*	*F*	*Power*	*f*
Males, *n* (%)	8 (44.44)	4 (22.22)	–	–	0.157	–	–	–
Age, years, mean (SD)	68.06 (8.99)	63.89 (6.57)	–	–	0.122	–	–	–
Weight, kg, mean (SD)	87.51 (15.52)	71.83 (13.87)	–	–	0.003**	–	–	–
Height, m, mean (SD)	1.69 (0.08)	1.67 (0.10)	–	–	0.630	–	–	–
Physical activity, h/week, mean (SD)	1.61 (2.12)	0.86 (1.16)	–	–	0.197	–	–	–
Knee pain, mean (SD)	4.54 (2.31)	0.00 (0.00)	–	–	–	–	–	–
Total number of steps analyzed, mean (SD)	18.74 (2.78)	16.21 (2.78)	2.53	0.49 to 4.58	0.017*	–	–	–
Gait speed/height	0.72 (0.09)	0.83 (0.09)	−0.11	−0.18 to −0.04	0.002**	10.82	0.923	0.582
$CV_{step\ length}$, %	3.28 (2.49)	2.81 (2.49)	0.47	2.09 to 4.48	0.601	0.28	0.009	0.095
Stance time, %GC	63.78 (2.19)	60.85 (2.19)	2.93	1.32 to 4.54	0.001**	13.74	0.968	0.655
Swing time, %GC	36.22 (2.21)	39.19 (2.21)	−2.97	−4.60 to −1.34	0.001**	13.86	0.969	0.658
Single support time, %GC	35.36 (1.99)	38.92 (1.99)	−3.56	−5.02 to −2.10	<0.001**	24.56	0.999	0.876
Total double support time, %GC	28.43 (3.70)	22.00 (3.70)	6.43	3.71 to 9.16	<0.001**	23.16	0.999	0.851

CV: coefficient of variation; GC: gait cycle; *P*: probability value (*$P \leq 0.05$, **$P \leq 0.01$ denote a significant difference) MD: mean difference; 95% CI: confidence interval of the mean difference; *F*: critical *F* value of the *F*-distribution (variance of the group means/mean of the within group variances); *f*: effect size; ANCOVA: analysis of covariance.
All gait parameters are presented as estimated marginal means (estimated standard deviation): ANCOVA adjusted for age and weight.

patients revealed that this mean group cluster solution largely originates from two distinct ways of clustering within that group: BAC 3 (mid-stance) is singled out in one part of the group (Figure 2(a)) and BAC 7 (mid-swing) is singled out in the other part of the group (Figure 2(b)).

Considering these individual differences within the patient group, in the next step, we determined the Euclidean distances between BACs 2 and 3 as well as between BACs 6 and 7 (smaller distances indicate higher similarity to the control group) to examine whether these differences in the gait-specific representation have distinct effects on actual gait parameters. Moreover, we determined the number of sequencing errors (as compared to the order of BACs in the control group) and the structural similarity (based on clusters formed below $d_{crit}=3.53$) of each patient's mental representation with the mean group cluster solution of the healthy controls controlled for the mean Euclidean distance between consecutive BACs (functional periods) as measure of structural quality of the mental representation (normalized to anchoring depth). Subsequently, these measures were submitted to individual analyses.

Correlation between spatio-temporal and temporophasic gait parameters and measures of the mental representation in gonarthrosis patients

Table 2 shows correlations between individual gait parameters and selected measures of the mental representation structure of the gait in patients with severe gonarthrosis. Correlation analyses revealed the relation between the number of sequencing errors in the mental representation structure of the gait (as compared to healthy controls) and gait variability, $CV_{step\ length}$, to be significant ($r=0.494$; $P=0.04$). That is, actual gait

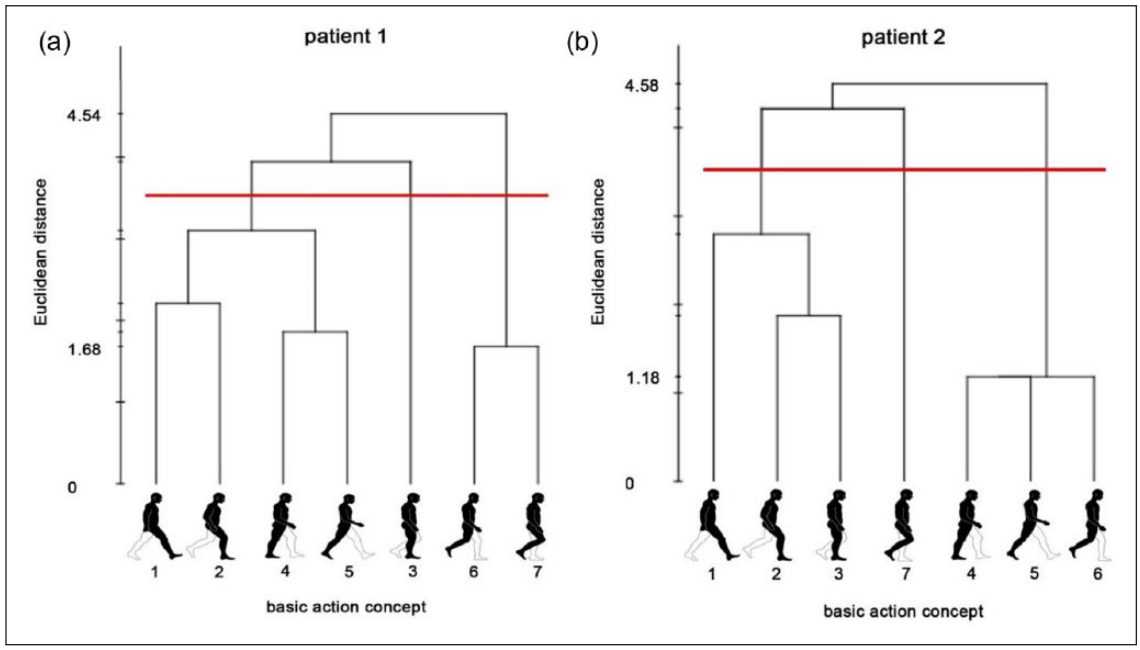

Figure 2. Dendrograms of two selected patients with severe knee osteoarthrosis. The gait-specific mental representation of patient 1 (age: 57 years, weight: 130 kg, height: 1.82 m, pain: 8.0) (a) differs from the control group in BAC 3 (mid-stance) which is singled out likely as a result of pain during weight-bearing with the affected leg. The gait-specific mental representation of patient 2 (age: 71 years, weight: 85 kg, height: 1.63 m, pain: 4.5) (b) differs from the control group in BAC 7 (mid-swing) which is singled out likely because of pain during bending the affected knee.

Table 2. Correlations between actual gait parameters (spatio-temporal and temporophasic) and selected measures of the mental representation of the gait in gonarthrosis patients.

	Structural similarity, Λ	sequencing errors	BAC 2–3 distance	BAC 6–7 distance
$CV_{step\ length}$, %	−0.015	0.494*	0.353	0.105
Gait speed/height	−0.134	−0.063	−0.054	0.325
Stance time, %GC	0.458§	−0.158	−0.164	–0.413§
Swing time, %GC	−0.458§	0.158	0.164	0.413§
Single support time, %GC	−0.368	−0.111	−0.297	0.591**
Double support time, %GC	0.462*	−0.020	0.097	−0.571**

CV: coefficient of variation; GC: gait cycle; BAC: basic action concept.
**$P \leq 0.01$, *$P \leq 0.05$, §$P \leq 0.10$.

variability increases with an increasing number of sequencing errors (as compared to healthy controls) in the gait-specific mental representation in gonarthrosis patients. Analyses revealed no significant links between the height-adjusted gait speed and the gait-specific mental representation (all $P > 0.19$). Analysis of the temporophasic gait parameters, however, revealed that patients' double support time was significantly associated with the structural similarity of their cluster solutions with healthy controls ($r = 0.462$; $P = 0.05$) and that patients' single ($r = 0.591$; $P = 0.01$) and double

support times ($r = -0.571$; $P = 0.01$) were associated with the Euclidean distance between BACs 6 and 7. That means that double support times are longer the better the individual gait-specific mental representation resamples the cluster solution of the healthy controls and that a greater distance between BACs 6 and 7, indicating that BAC 7 (mid-swing) is singled out, is associated with longer single support and shorter double support times in gonarthrosis patients.

Discussion

The primary aim of this study was to compare spatio-temporal and temporophasic gait parameters as well as the gait-specific long-term memory structures between knee osteoarthrosis patients and age-matched healthy control subjects. A secondary aim was to grow understanding of the role of mental representation for the human gait in general.

First, differences were found in kinematic gait parameters and in the mental representation of the gait cycle between the patient group and the control group. In line with previous research, the patient group showed a reduced gait speed[37–39] along with longer stance and double-support times[18,40] as compared to the control group. In addition, the gait-specific long-term memory structure differed between the patient and control groups. In contrast to previous work in healthy young and older adults[20] and to the control group tested in this study, mid-stance and mid-swing phases were not clustered together with preceding and following functional periods of the gait cycle in osteoarthrosis patients. That means, our data suggest that mid-stance and mid-swing are critical functional periods that are most affected in gonarthrosis patients' long-term memory structure. Moreover, this finding supports the assumption that (a history of) musculoskeletal injuries can lead to structural changes in the mental representation of the human gait.[20]

Second, the present results showed that the mental representation of the human gait is associated with actual gait performance in osteoarthrosis patients. In detail, double support times were positively associated with the structural quality of the mental representation. Thus, it appears that the prolonged double support times in patients with gonarthrosis, which are known as a compensatory mechanism to minimize or avoid postures associated with pain like during bearing the bodies weight solely on the affected limb,[9,10] depend on the quality of the mental representation. It can therefore be argued that a good mental representation of the gait is necessary to be able to flexibly adjust the gait pattern to altered situational constraints (here avoiding the disease-related pain), similar to what has been concluded for experts in the field of sports.[25,27] Moreover, step length variability was positively associated with the number of sequencing errors in the representation (as compared to control group), indicating that a less structured mental representation of the gait comes along with a higher gait variability. The study, thus, provides further evidence that actual walking performance relies upon (and/or forms) the mental representation structure of the human gait which in turn could be helpful for diagnosing, monitoring or even treating disease-related gait abnormalities.

This study does have some limitations that should be considered when interpreting our data. First, while 18 patients and 18 control subjects might provide sufficient power for the statistical comparison of both groups (power > 0.80 for all significant results), the sample sizes are rather small for the correlational analyses. Second, the last period of the gait cycle (terminal swing) was not included in the splitting procedure as pilot data have shown that terminal swing and initial contact (first period) are not clearly distinguishable from each other. Third, the present findings are limited to the affected (right) leg in patients with severe knee osteoarthrosis. There is the possibility that knee osteoarthrosis patients have a proper or better mental representation for the unaffected leg, which might aid in regaining a normal gait pattern during rehabilitation. However, as only patients suffering from right leg knee osteoarthrosis were included and, therefore, the right leg was emphasized during the splitting procedure (SDA-M), no such conclusions can be

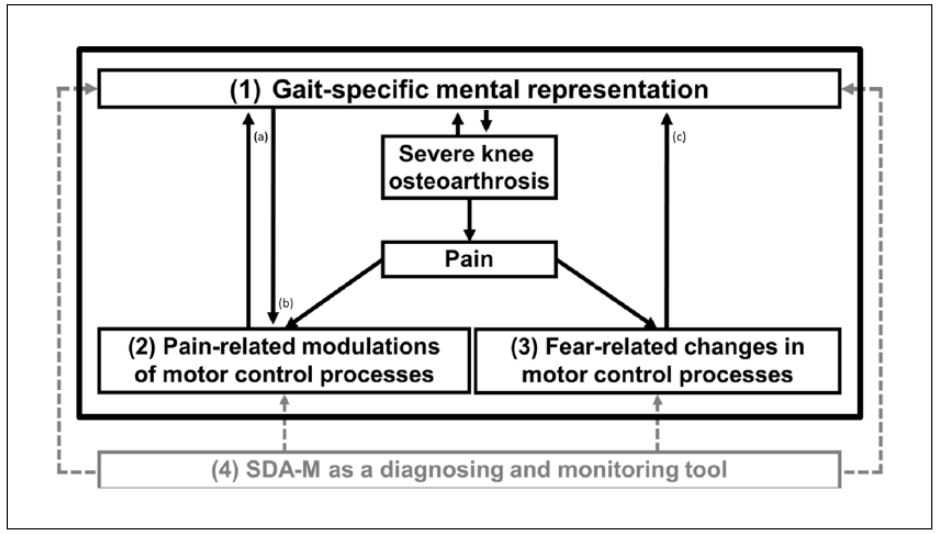

Figure 3. The mental representation could be a central issue during severe knee osteoarthrosis. The modulated motor control processes (ascending arrows) are associated with structural changes in the mental representation of the gait (1). The occurrence of pain can lead to pain-related modulations of motor control processes (2) and further (pain-induced) adaptations (a). In addition, fear-related changes in motor control processes (3) can result from avoidance of movement phases that are associated with previously experienced pain (stimuli). In consequence, the meaning and function of that one and all other action concepts within the mental representation might change (c). Furthermore, an improved mental representation helps to compensate gait abnormalities (descending arrow) (b). The SDA-M (4) provides information about the affected gait phase (basic action concept). The SDA-M could be a useful tool for clinicians to recognize changes in mental representation (1), especially in gait performance of patients with orthopedic diseases for diagnosing gait abnormalities or monitoring therapeutic treatments (dashed ascending arrows).

drawn based on the present data. Nevertheless, the SDA-M offers opportunities to optimize the rehabilitation (Figure 3).

Pain-related modulations of motor control processes

There is evidence that the occurrence of acute pain can modulate motor control processes during movement preparation and/or execution, that is, spinal and cortical excitability is likely to change significantly during or following painful events. Studies have shown that experimental pain led to a reduced quadriceps electromyographic activity[41,42] and Hoffmann reflex amplitude[43,44] indicating decreased spinal excitability and/or increased presynaptic inhibition of Ia afferents in healthy subjects.

With potential relevance to patients with severe knee osteoarthrosis, researchers demonstrated an increase in corticospinal excitability of the quadriceps muscle during acute experimental knee pain.[45] More specifically, a recent study showed a negative linear relation between joint pain intensity and quadriceps resting motor threshold in M1 in patients with severe knee osteoarthrosis.[46] These findings indicate that on one hand pain leads to inhibition in spinal pathways and on the other hand to higher excitability at subcortical or cortical levels. Pain thus seems to induce competing effects of inhibition and facilitation on different levels.[45] These pain-induced changes in movement-related cortical activation are described as a *protective mechanism* of the human body.[47,48] Consequently, the occurrence of acute pain caused by structural damage, swelling and tissue inflammation in

patients with severe knee osteoarthrosis[3] presumably affects gait-related cortico-motor control processes leading to (pain-induced) adaptations in the preparation and/or execution of walking actions that in turn lead to changes in the mental representation of the gait (see Figure 3).

Fear-related changes in motor control processes

Another explanation for pain-related physical performance changes could be fear and anxiety. Different models (i.e. the "activity" avoidance model or the "fear" avoidance model) characterized the relationship between fear of pain, further tissue damage and avoidance of normal return to activity; which can finally lead to deconditioning and disability.[49,50] In the "activity" avoidance model, it is argued that a previously neutral stimulus gets a negative meaning. Injuries result in an automatic response of a sympathetic activation, including fear and anxiety.[49,50] In this regard, situations associated with previous pain or injuries get a negative meaning which subjects finally learn to avoid in the future (classical conditioning).[51] In accordance with this approach, different studies in low back pain patients reported positive associations between pain-related fear and changes in physical performance.[52,53] With regard to patients with severe knee osteoarthrosis, there is an evidence for fear-induced activity avoidance behavior using the Tampa Scale for Kinesiophobia.[54] Another study has shown the relation between fear, anxiety and depression and physical function in patients with severe knee osteoarthrosis and found anxiety and fear-avoidance beliefs to be linked to self-reported measures of physical performance.[55]

With regard to the present findings, it is important to note that the established avoidance behavior is said to be quite robust and resistant to reverse[49] suggesting that fear-induced activity avoidance affects higher-order control processes of movement planning and control (see Figure 3). Thus, it is likely that the presence of acute pain and the attempt to avoid future pain results in modifications to the long-term memory representation of the respective motor action. More specifically, the (fear-induced) avoidance of single movement phases that are associated with previously experienced pain (stimuli) could change the meaning and functionality of that one and all other action concepts within the mental representation of a certain motor action in long-term memory.

The results of this study indicate that the mid-stance (Figure 2(a)) and mid-swing phase (Figure 2(b)) may be critical phases in patients with severe knee osteoarthrosis within the gait-specific mental representation. This finding is in line with biomechanical analyses of gait that have found modulations in kinematic and kinetic parameters in these specific gait phases.[13,56,57] Based on the results of Messier et al.,[57] patients with severe knee osteoarthrosis exhibited decreased knee joint range of motion during the swing phase. Astephen et al.[56] found increased knee adduction moments in the mid-stance phase. Furthermore, Al-Zahrani and Bakheit[13] showed a delayed onset of neuromuscular activation for the rectus femoris, medial hamstring, tibialis anterior and gastrocnemius muscles during the mid-stance and mid-swing phases in patients with severe knee osteoarthrosis. These gait modulations are primarily a result of pain due to cartilage erosion, subchondral sclerosis, subchondral cysts and meniscal degeneration of the knee joint.[12,58] Especially in the mid-stance phase, patients with severe knee osteoarthrosis avoid pain during weight-bearing by reducing knee joint loading.[18] Long-term memory structures of two selected patients with severe knee osteoarthrosis are presented in Figure 2. The structural differences between the two gait-specific mental representations indicate that the gait phase which is most affected by severe knee osteoarthrosis can differ between patients, probably depending on where the patients have experienced greater pain, that is, during weight-bearing with the affected leg or during bending the affected knee. However, all patients have in common that they singled out either one of these two or even both critical BACs indicating a disease-related change in mental representation.

Use of the SDA-M as a diagnosing and monitoring tool

Following up on studies introducing the use of mental representations of motor actions by means of SDA-M in elite sports[25,27] and in patients with stroke,[28] results of this study indicate that the SDA-M could be a useful tool to diagnose, monitor and treat gait abnormalities in patients with gonarthrosis and related diseases affecting the lower limbs. That said, clinicians and physical therapists should know how to use the tool. The comparison of the patients' SDA-M results with the control group clustering provides information about the affected gait phase (BAC). All gait phases linked to each other below the red line are functionally connected in long-term memory. Exercise therapies should focus on improving gait in the affected gait phase in order to suspend the pain-related and/or fear-induced avoidance behavior (deconditioning) and improve the qualified use of compensatory gait patterns. Therefore, the SDA-M could be a useful tool for clinicians to recognize changes in gait performance in patients with severe knee osteoarthrosis and other orthopedic diseases. It could be used for diagnosing gait abnormalities and monitoring therapeutic treatments. Thus, the SDA-M could inform therapists regarding which treatment best suits the individual circumstances of the patients (i.e. are long-term memory structures affected and if, which are most affected). Also, it could be of use for cognitive treatments (i.e. to directly alter long-term memory structures) in addition to the conservative and operative treatments of severe knee osteoarthrosis. In combination with the previously reported muscle weakness, the disease-related changes in the gait-specific mental representation likely promote the risk of falls which is a main reason for immobility, premature nursing and substantial rates of morbidity and mortality.[59] That said, analyzing the mental representation of the gait with SDA-M could be implemented as a diagnosing tool in practice guidelines for fall prevention in general.

In conclusion, the SDA-M may be an opportunity to examine the mental representation of walking abnormalities in patients with severe knee osteoarthrosis and other orthopedic diseases. Considering the present results, further research is needed to examine the modulations of mental representation in primary and secondary knee osteoarthrosis in association with pain and pain-related fear. Furthermore, it is of interest whether and when structural changes in long-term memory occur after, for example, meniscus rupture, ligament injuries and cartilage defects. In addition, studies should examine the effect of exercise interventions on mental representation of gait and regaining normal gait patterns in patients with severe knee osteoarthrosis and other orthopedic diseases.

Clinical Messages

- The gait-specific mental representation differs between patients with severe knee osteoarthrosis and healthy controls.
- Mid-stance and mid-swing phases are critical functional periods within the mental representation of the gait in patients with severe knee osteoarthrosis probably induced by disease-related painful events.

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Author contributions

T.S., A.M.-M. and M.B. developed the study concept, and all of these authors contributed to the design in collaboration with R.J., W.M., R.B. and R.S. R.J., M.B. and A.M.-M. collected the data and analyzed it in collaboration with T.S. R.J., A.M.-M. and T.S. wrote the first draft of the manuscript. M.B., W.M., R.B. and R.S. helped to edit and revise it. All authors approved the final, submitted version of the manuscript.

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