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Mapping-Based Dosage Selection for Multi-Parameter, Subject-Specific Gait Retraining

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ABSTRACT Gait retraining to reduce knee loading has been proposed as a conservative treatment option for early-stage knee osteoarthritis. Mounting evidence suggests that a subject-specific approach may be most effective for ensuring consistent knee loading reductions across all individuals within a population. However, it is currently unclear how to determine the required dosage selection type and amount to both reduce knee loading and satisfy individual preferences. To overcome this challenge, we introduce a novel, mapping-based dosage selection approach to systematically determine multi-parameter gait modifications to reduce knee loading while maintaining individual user preference. In this approach, individuals first explore different dosages of multi-parameter gait modifications, and then a resulting visual map is displayed with a subject-specific dosage selection zone for the target knee loading reduction. Subjects then self-select a preferred gait within their dosage selection zone. To evaluate the feasibility of this approach, fifteen healthy subjects performed walking trials on a treadmill involving various dosages of gait modifications to foot progression angle and step width. Subjects quickly selected the subject-specific gait modifications via mapping-based dosage selection during a single 6 min trial, which reduced the knee adduction moment by an average of 14.2%. Resulting subject-specific gait modifications varied, with 6 subjects selecting only toe-in, 5 subjects selecting both toe-in and increased step width, 2 subjects selecting only toe-out, 1 subject selecting both toe-out and increased step width and 1 subject selecting only increased step width. Average perceived exertion was "fairly light" (index was 10.5±2.2). The presented mapping-based dosage selection approach could provide a systematic and practical means to determine subject-specific gait modifications while maintaining individual preferences.

INDEX TERMS Gait retraining, KAM, FPA, step width, subject-specific

I. INTRODUCTION

Gait retraining has been proposed as a potential conservative treatment alternative for knee osteoarthritis [1], [2]. Modified gait patterns can lower knee loads [3]–[5] and lead to increased knee function and reduced knee pain [6], [7]. The knee adduction moment (KAM) is highly correlated with medial knee contact forces [8], [9], and has been linked with the presence, severity, and progression of medial compartment knee osteoarthritis [10]–[12], and thus, reducing the KAM often is often a primary objective of gait retraining [4], [5], [13].

Biofeedback gait retraining has been shown to be effective in reducing KAM [5], [14]. There are two primary approaches to biofeedback gait retraining to reduce the KAM: direct biofeedback of the KAM and indirect biofeedback of secondary gait parameters that influence the KAM. In the first approach, direct biofeedback of the KAM measurement is provided directly to subjects, and subjects self-explore gait modification strategies that can reduce the KAM value provided [15], [16]. The mechanism of direct biofeedback is straightforward but has some limitations. One problem is that KAM measurement can be more complex, requiring simultaneous ground reaction force and kinematics data only suitable for laboratories with this equipment. Another problem is that subjects may be unable to self-explore new strategies unless they have already received training with specific modifications [17], and they may be unable to remember the specifically selected strategy after training [15]. In the second approach, indirect biofeedback of a secondary gait parameter that influences the KAM is provided and instructs subjects on a specific gait modification strategy. Typically, specific gait parameters are pre-selected prior to testing based on effectiveness and feasibility of implementation [18]. Previously suggested specific gait modification strategies include increasing medio-lateral trunk sway [19], [20], rotating the foot internally (toe-in gait) [21] or externally (toe-out gait) [7], [22], stepping wider [23] or narrower [24], moving the knee medially (medial-thrust gait) [25], reducing the lateral plantar pressure [26], or training multiple parameters simultaneously [27]. While these strategies have all demonstrated varying degrees of effectiveness in reducing the KAM, it is unclear which strategy or combination of strategies is most practical and effective.

In addition, while training the same type and dosage of gait modification is the most straightforward method of reducing the KAM on average, this typically leads to significant variation in effectiveness among individual subjects within a given population [7], [28]. This variation in effectiveness may be due to differences in individual muscle activation strategies [29], bone alignment [23] or secondary kinematic changes [30]. Thus, many researchers have suggested subject-specific gait retraining strategies for more effective reduction of the KAM across individuals within a population [31]–[33].

There are several approaches to implementing subject-specific gait retraining. The simplest method may be to implement subject-specific gait modification types, give a general dosage instruction, and then select the modification resulting in the largest KAM reduction [31]. This approach provides subject-specific training targets but does not account for dosage control. For example, the knee load might not be reduced enough if the dosage is too low or the new gait might be needlessly uncomfortable if the dosage is too high. Another approach would be to explore many candidate dosages for a given gait parameter change and then pick the most effective dosage [32]. Alternatively, it is possible to build a data-driven model to update the target dosage for each trial based on the previous trial's performance [27]. These methods may be more effective at finding the optimal dosage but require multiple trials and could involve lengthy post-processing, which may not be feasible for practical implementation. Also, only targeting the optimal KAM reduction and disregarding gait parameter change dosage amounts could lead to awkwardness and fatigue [6], [15], [34], which could result in prescribed gait modifications that are uncomfortable or require a significant amount of extra effort.

The purpose of this paper is to introduce a visual, mapping-based dosage selection approach for subject-specific gait retraining involving simultaneous changes to multiple gait parameters. The proposed approach is automated, eliminating the need for any post-processing, making it potentially more suitable for widespread use. We sought to determine whether subjects could utilize this approach to select subject-specific gait modification dosages to reduce the KAM through multi-parameter gait changes. We hypothesized that subjects could self-select and adopt subject-specific gait modifications and dosages in a single testing session resulting in reduced KAM. We further hypothesized that the selected dosages would vary in amount and type across subjects.

II. METHODS

A. SUBJECTS

Fifteen healthy subjects (age: 25.5±2.1, BMI: 21.6±1.9, all-male) participated in this study after giving informed consent prior to the start of the experiment. The exclusion criteria were: a) body mass index (BMI) greater than 35 kg/m^2, b) history of knee or hip surgery or c) neurological conditions affecting ambulation. The study was approved by the Shanghai Jiao Tong University affiliated Sixth People's Hospital Institutional Review Board (YS-2018-012) and conformed to the Declaration of Helsinki.

B. EXPERIMENTAL SET-UP

Reflective markers were placed across the body at the following locations: head of the second metatarsal, head of the fifth metatarsal, calcaneous, malleoli, femoral epicondyles, anterior and posterior superior iliac spine, acromion and C7. Four additional marker clusters were used on each limb to prevent data drop. FPA, step width and KAM were processed in real-time at 100 Hz with MATLAB (2016b, The MathWorks, USA) from optical marker data via 16 motion capture cameras (Vicon, Oxford Metrics Group, UK) and ground reaction forces via a split-belt an instrumented treadmill (Bertec, Ohio, USA). A 32-inch monitor (C32H711QEC, Samsung, South Korea) was placed in front subjects to provide visual feedback during testing. FPA was defined as the averaged angle during foot flat phase for each step between the line from the calcaneous to the second metatarsal and the line of progression [35] (toe-out defined as positive); step width was defined as the distance between both ankle joint centers in the coronal plane during initial double support [28]; KAM was defined as the moment of the ground reaction force to the knee joint center in the adduction direction in the shank frame and normalized by height*weight [36]. The right leg was selected as the training leg for all subjects. The walking speed was 1.0 m/s for all trials.

C. EXPERIMENTAL PROTOCOL

The experimental protocol for mapping-based dosage selection includes four phases: Baseline, Exploration, Self-selection and Retention (Fig. 1). The four phases were performed sequentially during a single trial. Subjects initially performed practice walking trials for 5 minutes on the tread-

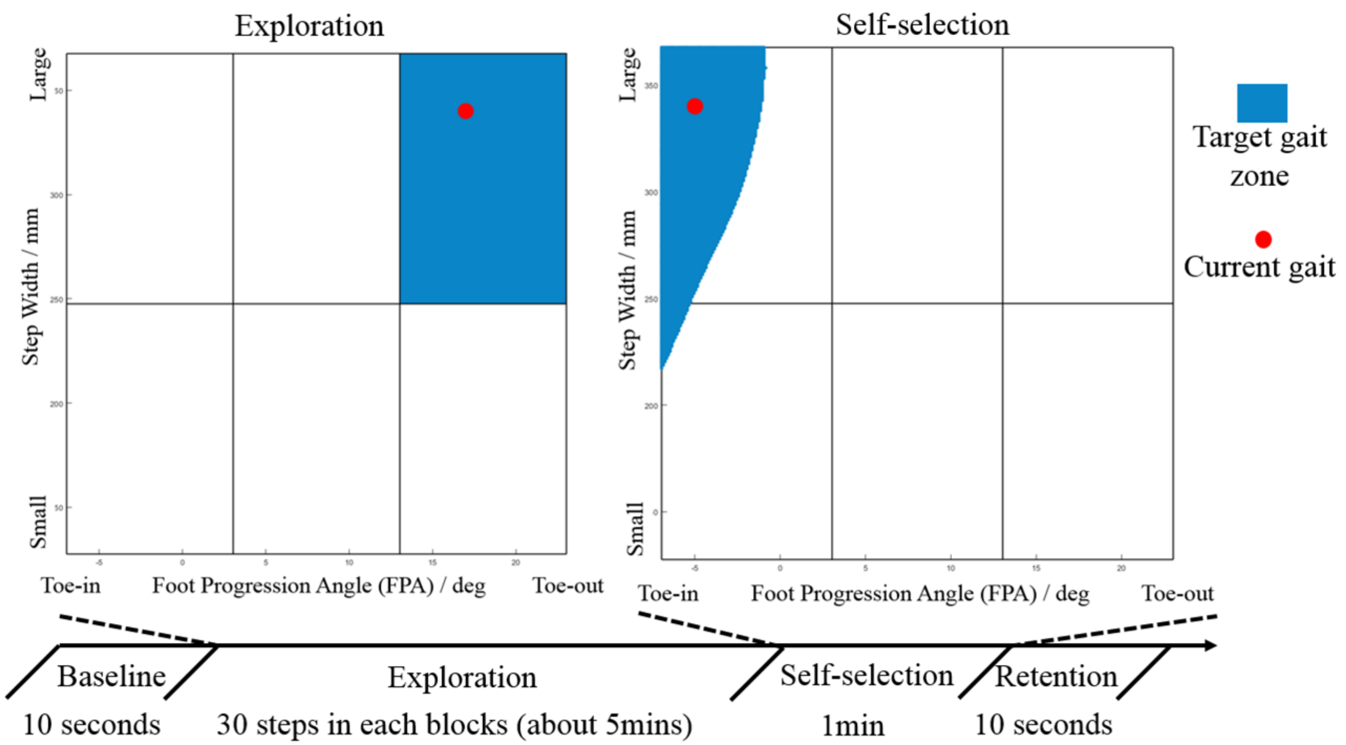

FIGURE 1. The experimental protocol includes Baseline, Exploration, Self-selection and Retention phases. During the Baseline phase, subjects were instructed to walk normally. During the Exploration phase, real-time visual feedback was provided to instruct subjects to explore different gait modifications. The blue area is the target gait zone, and the red dot represents the real-time gait parameters for the current step. During the Self-selection phase, a subject-specific blue area was automatically computed to reduce the knee adduction moment (KAM) by a target amount for each individual, and subjects were instructed to self-select a comfortable gait within that region. During the Retention phase, subjects maintain the self-selected new gait for 10 seconds without feedback.

mill while receiving real-time visual feedback to become familiar with the system before the testing trial.

a: Baseline

Subjects were first instructed to walk as normally. The last 7 steps of FPA, step width and KAM were calculated and averaged as the baseline. No feedback was provided in this phase.

b: Exploration

Real-time visual feedback was provided to subjects to inform gait changes relative to baseline parameters including for FPA: straight (-5deg to 5deg), toe-in (-15deg to -5deg) and toe-out (5deg to 15deg), and for step width: normal (-60mm to 60mm) and increased (60mm to 180mm); there were thus six total multi-parameter gait modifications. The blue area (Fig. 1) was the target gait zone shown on the screen that indicated which gait modifications to explore. The gait modifications were randomly ordered, and each required at least 30 valid steps before allowing subjects to switch to the next target gait. The red dot represented the current gait parameters; if the result was out of the screen, the dot would turn grey and appear at the nearest edge. During this phase, subjects went through each gait modification combination and experienced how it feels. All the FPA, step width and KAM data during this phase were captured to build the subject-specific visual KAM reduction map.

c: Self-selection

Data collected during Exploration phase testing (Fig. 2a) was used to automatically generate a KAM reduction map (Fig. 2b) using the Locally Weighted Scatterplot Smoothing (LOWESS) fitting method [37] - a type of local polynomial regression with distance-related weight defined as:

$$w\left(X\right)=\left(1-\left|d\right|^{3}\right)^{3} \tag{1}$$

where X is the point that needs to be fitted, which are the FPA value and step width value in this study normalized by MIN and MAX values; d is the distance of a given data point from the fitted point; and $w(X)$ is the weight of that given data point. The cost function could then be weighted by distance similar to least-squares linear regression (Equation 2). 50% of the closed data is factored in to the equation, thus N equals half of the total data set size. The cost function is defined as:

$$Cost_X(A)=\sum_{i=1}^{N}\left(KAM_i-A\hat{X}_i\right)^T w_i(X)\left(KAM_i-A\hat{X}_i\right) \tag{2}$$

where $\hat{X}_i$ is the ith given data point, A is the fitting parameter, and $Cost_X(A)$ is the fitting result. Then the KAM of the fitted point was estimated as:

$$\widetilde{KAM}=\tilde{A}X \tag{3}$$

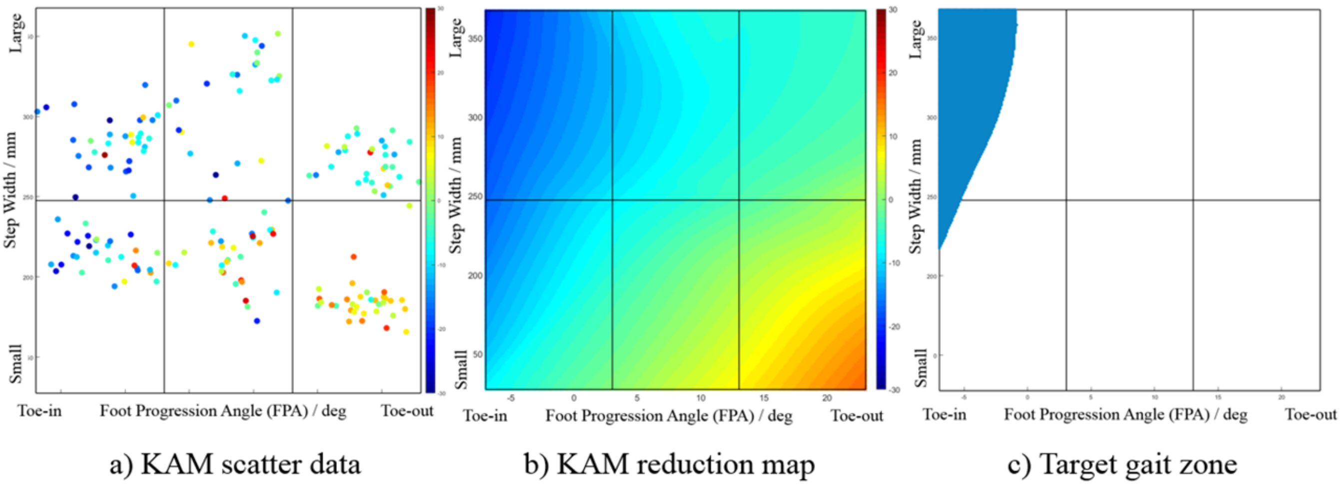

FIGURE 2. Examples of experimental data. a) raw data collected in the Exploration phase, in which the darkest red represents 30% of KAM increase and the darkest blue represents 30% of KAM reduction. b) KAM reduction map generated with the Locally Weighted Scatter plot Smoothing (LOWESS) fitting method. c) target gait zone specific to each subject based on the target KAM reduction.

Where $\tilde{A}$ minimizes the cost function $Cost_X(A)$, $\widetilde{KAM}$ is the estimated KAM at point X. A target gait zone (the blue area in Fig. 2c) was calculated based on the prediction that the KAM would be reduced 15%. If there was no area with a 15% reduction, the threshold was reduced to 10% and the target gait zone recomputed; if there was no area with a 10% reduction, the threshold was again recomputed at a 5% reduction. All subjects had a target gait zones of at least a 5% reduction. The visual feedback remained active during this phase to train subjects to control their gait (the red dot) in the target gait zone. Subjects were instructed to select the most comfortable and acceptable spot in the target gait zone.

d: Retention

Subjects maintain the self-selected new gait during the retention trial and the final 7 steps of were collected and analyzed to determine retention results.

D. SURVEY

After the walking trials were complete, subjects answered three subjective questions: 1) Difficulty: “How difficult did you feel performing the new gait?” Possible answers ranged from 0-10 points, where 0 was “No difficulty” and 10 was “Unable to perform” [7]. 2) Awkwardness: “How awkward did you feel performing the new gait?” Again, answers ranged from 0-10 points, where 0 was “Not awkward at all” and 10 was “Totally unacceptable” [15]. 3) Rating of perceived exertion: “How tired did you feel during testing?” Possible answers ranged from 6-20 points, where 7 was “Very, very light,” and 19 was “Very, very hard” [38].

E. DATA ANALYSIS

FPA, step width and KAM for both baseline gait and the self-selection gait during the retention phase were compared. RMSE (root-mean-squared error) and R^2 (R-square) were computed to quantify the quality of LOWESS, by comparing it with linear and quadratic fitting methods. To determine if there were statistical differences between baseline gait and self-selected gait, a student’s t-test was performed for each subject, the last seven steps of data for each gait were used. A one-way repeated measures ANOVA was performed overall. The statistical significance was defined as $p<0.05$. All data analysis was performed using MATLAB (The MathWorks, Natick, MA).

III. RESULTS

Self-selected gait patterns during the Retention phase were in the respective target gait zones for ten of the subjects and located at the boundary of the target gait zones (within 5%) for the remaining five subjects. The overall KAM of self-selected gait was significantly reduced compared with baseline ($p<0.05$), and the average reduction was 14.2% (Table 1). Subjects had exhibited significantly different KAM maps (Fig. 3). Subjects selected different gait modifications; six subjects selected only toe-in, five subjects selected both toe-in and increased step width, two subjects selected only toe-out, one subject selected both toe-out and increased step width and one subject selected only increased step width. (Fig. 4). The average testing time for the full trial was 5.3±0.3min, and the max trial time was 5.8 min. The awkwardness index was 7.1±2.0, the difficulty index was 4.9±2.5 and the rating of perceived exertion index was 10.5±2.2. The RMSE of the LOWESS fitting method was 0.28±0.05, which is significantly lower than linear (0.29±0.05, $P<0.05$) and quadratic (0.29±0.05, $P<0.05$) fitting methods. The R^2 of the LOWESS fitting method was 0.34±0.19, which is significantly higher than linear (0.27±0.20, $P<0.05$) and quadratic (0.31±0.20, $P<0.05$) fitting methods (Fig. 5).

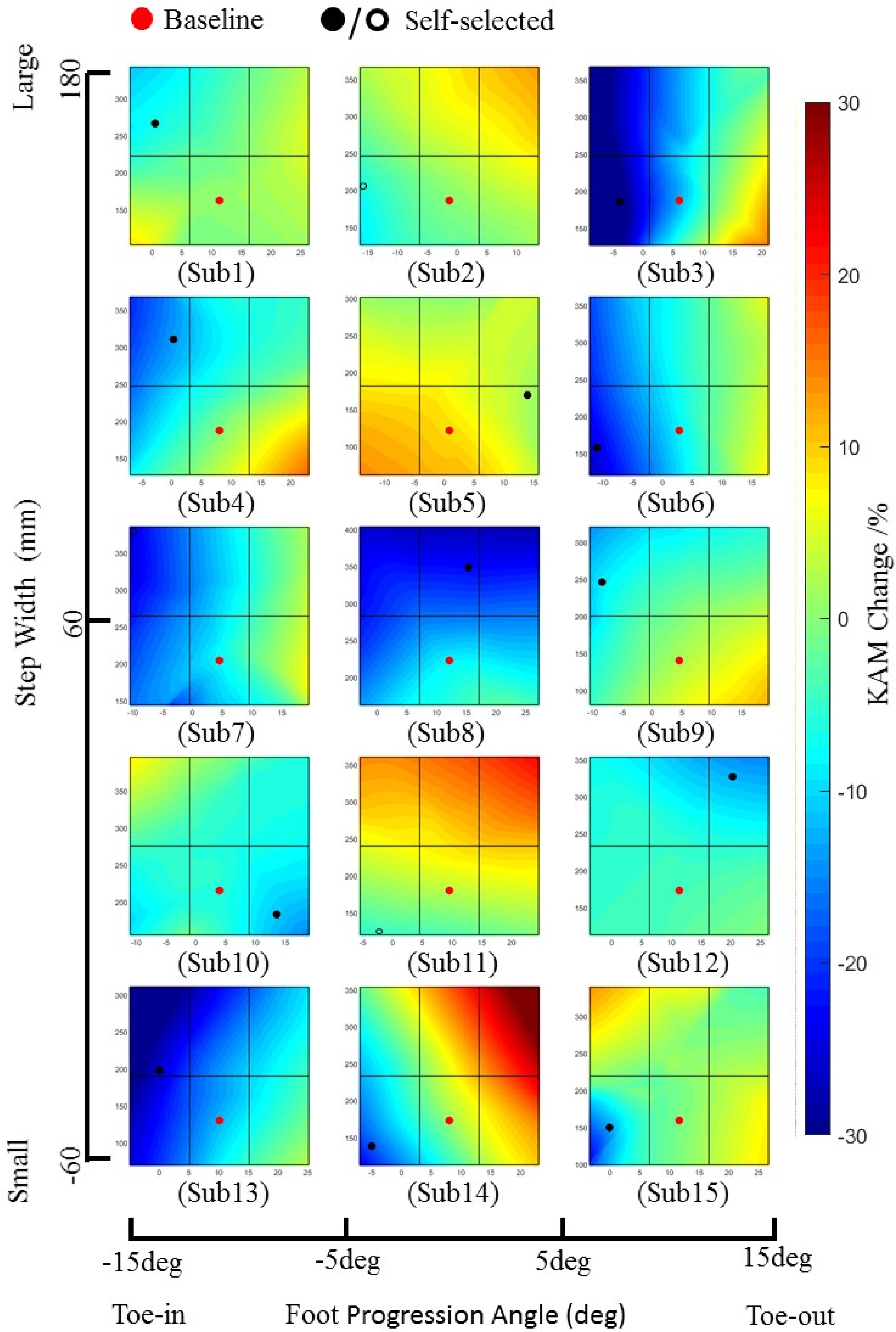

FIGURE 3. KAM mapping results for each subject. The red dots in each figure represent the baseline gait, and the black dots represent the self-selected gait. If the self-selected gait was out of the scope, a hollow black dot was placed at the closest edge.

TABLE 1. Baseline gait (Base), subject-specific gait (SS) and the difference (diff). Positive FPA values indicate external rotation from the direction of forwarding progress. Bold font represents statistical significance ($p < 0.05$).

Subject	FPA (deg)		Step width (mm)		KAM (normalized)	
	Base/SS	diff	Base/SS	diff	Base/SS	diff
1	10.8/0.5	**-10.3**	165/271	**106**	3.53/3.14	**-11.0%**
2	-1.0/-17.6	**-16.6**	189/202	12	3.73/3.19	**-14.7%**
3	6.0/-3.8	**-9.8**	189/185	-4	3.42/2.40	**-29.9%**
4	8.0/0.7	**-7.2**	187/305	**118**	2.82/2.46	**-13.1%**
5	0.8/14.4	**13.6**	122/170	**48**	2.96/3.25	9.8%
6	3.2/-10.7	**-13.8**	18/157	**-24**	3.64/2.77	**-24.1%**
7	4.5/-10.8	**-15.3**	203/363	**160**	2.26/1.81	**-19.7%**
8	12.3/15.5	**3.2**	223/341	**118**	4.38/2.85	**-35.0%**
9	4.4/-7.9	**-12.3**	140/234	**95**	2.29/2.18	-5.0%
10	3.9/13.1	**9.2**	217/191	**-26**	2.54/2.41	-4.8%
11	10.0/-2.7	**-12.7**	175/117	**-58**	3.89/3.95	1.4%
12	11.1/19.7	**8.6**	173/328	**155**	3.58/3.32	-7.1%
13	9.6/-0.1	**-9.7**	127/220	**73**	3.57/2.22	**-38.0%**
14	7.9/-6.1	**-14.0**	172/136	**-36**	3.17/2.18	**-31.3%**
15	11.7/-0.1	**-11.8**	160/151	-7	2.75/2.74	-0.1%
Average	6.9/0.3	**-6.6**	175/223	**47**	3.24/2.72	**-14.4%**

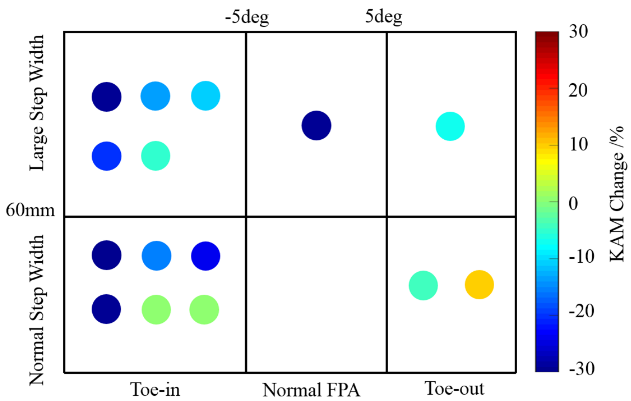

FIGURE 4. Self-selection results. Each circle represents the self-selected gait modification for one subject. Colors represent the degree of change in KAM. Results are grouped based on gait modification type.

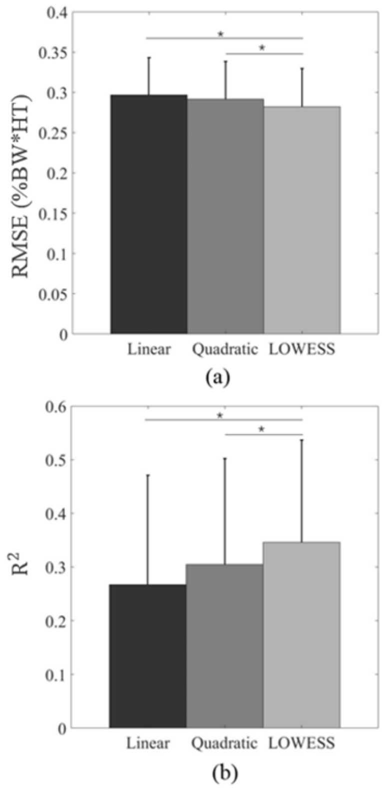

FIGURE 5. Quality of fitting. The LOWESS fitting method was significantly better than the quadratic method and linear method as it exhibited lower RMSE and higher R^2. Asterisks represent statistical significance.

IV. DISCUSSION

This study presents a mapping-based dosage selection approach for gait retraining. This method was performed in a single trial without the need for manual post-processing. A subject-specific KAM map was generated with the data in the Exploration phase, and a gait retraining target gait zone was selected. Subjects had the freedom to select their preferred gait modification in the target gait zone, which not only met the required KAM reduction but also optimized the acceptance of the new gait. All the subjects' self-selected gaits were located in or near the target gait zone, and the KAM of target gait was significantly reduced by 14.2% compared with baseline gait on average, which supports the first hypothesis that subjects could select subject-specific gait modifications in a single testing session resulting in reduced KAM. All five different gait modification patterns have been selected, and even the most commonly-selected pattern (only toe-in) only accounted for 40% of the subjects (Fig. 4), which supports the second hypothesis that the selected dosage would resulted in a variety of different across the subjects. The average rating of the perceived exertion index was 10.5, which is between "Very light" and "Fairly light," which indicates that the test is easy to perform.

Dosage selection results varied widely between subjects, which again supports the importance of subject-specific gait retraining. Seven subject selected large step width, indicating increasing step width could be an effective option but not necessarily for all people. Previous research only showed the KAM would be reduced on average when step width was wider [23], which is the same as the present study. No individual data were demonstrated in that study. 73.3% (11/15) of subjects selected toe-in. In a previous subject-specific gait modification study, 45% of subjects selected toe-in only based on KAM reduction [32] and 40% of subjects selected toe-in only in the present study. The average KAM reduction was 14.2% in the present study, which is similar with previous that only toe-in (13%) [21], only toe-out (10%) [39] and subject-specific gait retraining (18.6%) [32], but it is much less than combined toe-in and wider step width (38%) [23]. However, the combined study was performed overground, which may be very different from on treadmill [40]. As far as we know, ours was the first method that selected subject-specific gait modification dosage for reducing KAM in one trial and the average time of the trial was less than six minutes. Previous research required three trials [27], five trials [35], or seven trials [32], and all of them needed post-processing. The time of these experiment was not reported.

The KAM map was estimated by fitting the FPA and the step width to the KAM. LOWESS fitting method was used in the experiment but the R^2 of LOWESS fitting only was 0.35, indicating that except for the FPA and step width, other gait parameters were not under control. However, because more parameters are more difficult to learn, most researchers have only studied one parameter. Linear or quadratic models to fit the KAM with kinematic parameters are very straightforward [27], but the real relationship was quite complicated. Including the weight of distance could improve the ability of nonlinear regression. Comparing LOWESS with linear and quadratic fitting methods, the quality of fitting was significantly higher for LOWESS (the R^2 was higher and the RMSE was lower). Another way is to build a subject-specific inverse dynamics model [8], [41]; this method should have higher accuracy, but it takes more time and may not be very practical.

This study presents a gait retraining dosage selection method. Reducing knee loading as an alternative for knee osteoarthritis treatment was proposed as one example application. Other potential applications could be studied with minimal changes such as gait retraining to prevent running injuries [42] and stroke rehabilitation [43]. This study validated the mapping-based dosage selection method for two gait parameters. One parameter or more parameters also could potentially be trained. For three gait parameters, researchers may need to explore a three-dimensional visual map, and for four or more parameters, they may need to explore using multiple maps. More similar studies could be explored in the future.

Despite the overall average KAM reduction of 14.4%, only nine subjects whose KAM reduction showed statistical significance. Previous research has also shown this phenomenon, such as a subject-specific gait retraining study in which several subjects could not significantly reduce their KAM [32]. The reason of gait retraining does not help every individuals is unclear, though one potential factor could be that their gait is already optimized and there is little or no room to improve. Further research is needed to explore this phenomenon. In addition, in this experiment, the training time was relatively short and only immediately retention was studied. Five subjects' selected gait patterns were very close to the target zone but not in the zone which indicates that the gait control still needs to improving potentially with more practice. The effectiveness after long-term gait retraining remains unknown, through previous research on indirect biofeedback gait retraining with a traditional dosage method demonstrates positive results [44], [45]. The presented method requires real-time gait kinematics and kinetics measurements, which relies on relatively expensive optical motion capture equipment and an instrumented treadmill. However, kinetics are not needed after dosage selection, and gait kinematics could be measured [46], [47] and retrained [48], [49] via wearable systems, which could be a less expensive, more convenient alternative in daily life training. The current experiment only included male subjects, though future work should test female subjects to determine whether these results can be extended to both genders.

V. CONCLUSIONS

This study presented a mapping-based subject-specific gait retraining dosage selection method for gait retraining to reduce the KAM. In this approach, a subject-specific KAM reduction map and a target gait zone were generated, and subjects self-selected their preferred dosage in the target gait zone as the target gait. This method neutralized the problems of finding an effective and acceptable gait retraining method for the subjects. It is also quick and has no post-processing, thus it could be a more practical method for widespread use. More research needs be done to test the long-term effectiveness of this method.

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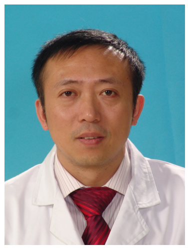

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