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Biomechanical assessment of patellar tendon advancement in patients with cerebral palsy and crouch gait

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ABSTRACT

Background: Patellar height is a valuable measure to evaluate the effect of patellar tendon advancement (PTA) on knee function. In the literature, there is no validated procedure to measure the patellar height. In this study we aimed to (1) determine the patella position through musculoskeletal modeling, (2) investigate the effects of two surgical procedures applied for PTA, and (3) assess the effect of PTA in combination with single-event multi-level surgery (SEMLS) on the knee kinematics of patients with cerebral palsy (CP) and crouch gait.
Method: Three-dimensional gait and X-ray data of children with CP and crouch gait were retrospectively analyzed if they had received a SEMLS in combination with PTA (PTA group, $n = 18$) or without PTA (NoPTA group, $n = 18$). A computational musculoskeletal model was used to quantify patella position, knee extension moment arm, and knee kinematics pre- and postoperatively.
Results: Patellar height significantly decreased in the PTA group ($P = 0.004$), while there was no difference in the NoPTA group ($P > 0.05$). The bony procedure for PTA provided a better Insall–Salvati ratio than the soft tissue procedure. The peak knee extension moment arm significantly increased in the PTA group ($P = 0.008$). In terms of postoperative knee joint kinematics, the PTA group was closer to typically developed children than the NoPTA group.
Conclusion: Musculoskeletal modeling was found to be an effective tool for the determination of the patellar height. PTA improved the patella position, knee extension moment arm, and knee kinematics and was an effective procedure for the surgical management of crouch gait in patients with CP.

1. Introduction

Crouch gait is a frequent gait pathology in children with cerebral palsy (CP) which is described by excessive hip and knee flexion [1–3]. Patella alta commonly exists in children with CP and crouch gait and is often associated with inadequate knee extensors [1,4–6]. Single-event multilevel surgery (SEMLS), which is an umbrella term for all combinations of several surg-

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eries, is regarded as the standard procedure for improving gait and functions of CP patients [7–9]. Among SEMLS methods, patellar tendon advancement (PTA) is typically preferred for the treatment of crouch gait [10].

PTA is performed to enhance the quadriceps moment arm, consequently producing the necessary knee extension moment during gait. PTA can be performed by patellar tendon shortening or distal advancement of the tibial tuberosity [11]. Das et al. and Stout et al. revealed the advancements in knee kinematics and quadriceps strength when PTA was performed [4,12]. Moreover, they reported that PTA should be performed independently of patellar height. Novacheck et al. and Klotz et al. reported better outcomes with PTA in the management of crouch gait [13,14]. Boyer et al. showed that SEMLS including PTA improved knee function in gait at long-term periods, while these benefits did not affect knee pain or activity [11]. Because some patients show residual crouch, debates about the requirement for PTA remain [4,15]. PTA is generally implemented in combination with other surgical procedures. Hence it is difficult to objectively evaluate the isolated effect of PTA. Furthermore, uncertainty regarding patella height in patients subjected to PTA remains [4]. Therefore, there is no consensus on the effect specifically of PTA on the outcome [4,9].

Patellar height is a valuable measure to evaluate the effects of PTA on knee function [10]. In a musculoskeletal modeling and simulation study, Lenhart et al. found that patella position had a considerable effect on the patellar tendon moment arm, and hence, torque-producing capacity of the quadriceps [16]. Patella position can be determined using several radiographic imaging modalities such as Insall–Salvati (IS) ratio [17,18] or Koshino Index [19]. However, these modalities require the radiographical image that should be taken at a specific knee angle: particularly 30° of flexion [20–22]. Because patients may have different hip and knee joint angles during X-ray measurements, it is difficult to determine and evaluate the location of the patella objectively using these indices. In the literature, there is no validated procedure to measure the patellar height. Therefore, utilizing gait analysis and musculoskeletal models may provide better accuracy when determining the effect of PTA.

Summarizing, in this retrospective study, we aimed to (1) objectively determine the patella position at high precision through X-ray and musculoskeletal modeling, (2) to investigate the effects of two surgical procedures applied for PTA, namely distal advancement of the tibial tuberosity and patellar tendon shortening on to the patella position, and (3) to monitor the surgical effect of PTA in combination with SEMLS on the knee kinematics of patients with CP and crouch gait.

2. Material and methods

2.1. Study design

A retrospective study was designed considering the database of the local University Hospital. This study was approved by the local ethical committee of the Faculty of Medicine (S-515/2019).

Children with CP were screened if they had undergone SEMLS with (PTA group) or without PTA (NoPTA group). Standard procedures in the context of CP and crouch gait in our hospital are femoral extension osteotomies or hamstring lengthenings to improve knee extension, and potentially a distal rectus femoris tendon transfer in case of delayed and reduced maximum knee flexion in swing. PTA was performed either as a bony procedure by distal advancement of the tibial tuberosity or via patellar tendon shortening. Inclusion criteria for both groups were (1) ability to walk without assistive devices or assistance by another person and (2) having gait, electromyography, and X-ray data for the preoperative and postoperative exams. The Gross Motor Function Classification System (GMFCS) level [23] was not considered as an inclusion or exclusion criterion.

A total of 458 patients with CP having SEMLS between 2002 and 2019 were considered (Figure 1). Twenty-one children were pre-selected for the PTA group and 34 children for the NoPTA group. To be able to objectively reveal the effect of PTA in the context of SEMLS, patients in both groups were paired such that they were as similar as possible in terms of demography and clinical history. The equivalent number of children were included for each group by matching them patient-by-patient. Matching of the patients was performed by giving priority to having similar (1) age, (2) maximum knee extension at stance, (3) maximum knee flexion at swing, (4) knee range of motion (RoM), (5) GMFCS level, and (6) gait profile score [24] in the preoperative examination. Major surgeries applied to the patients, which would affect the postoperative outcome, were also approved to be similar, except for PTA surgery. These surgeries were femoral extension and derotation osteotomies, hamstring lengthenings, and rectus femoris tendon transfers.

The process of determining the best group matches with respect to these matching criteria led to 18 patients (29 limbs) for the PTA group and 18 patients (26 limbs) for the NoPTA group. A flow chart regarding the determination of the groups is given in Figure 1.

The preoperative status and surgeries are listed in Table 1. There was no statistical difference between groups. Details regarding the applied statistical analyses are provided in the Data Analysis section.

2.2. Experimental protocol

Temporospatial, kinematics, and kinetics data of the patients were collected at self-selected walking speed preoperatively and 17.5 ± 5.4 months after surgery. Nineteen markers were applied according to a standard protocol (Plugin Gait; Oxford Metrics, Oxford, UK) and trajectories were recorded by a 12-camera Vicon motion analysis system (Oxford Metrics, Oxford, UK) at 120 Hz sampling frequency. The ground reaction force was recorded using force plates (Kistler Instruments, Win-

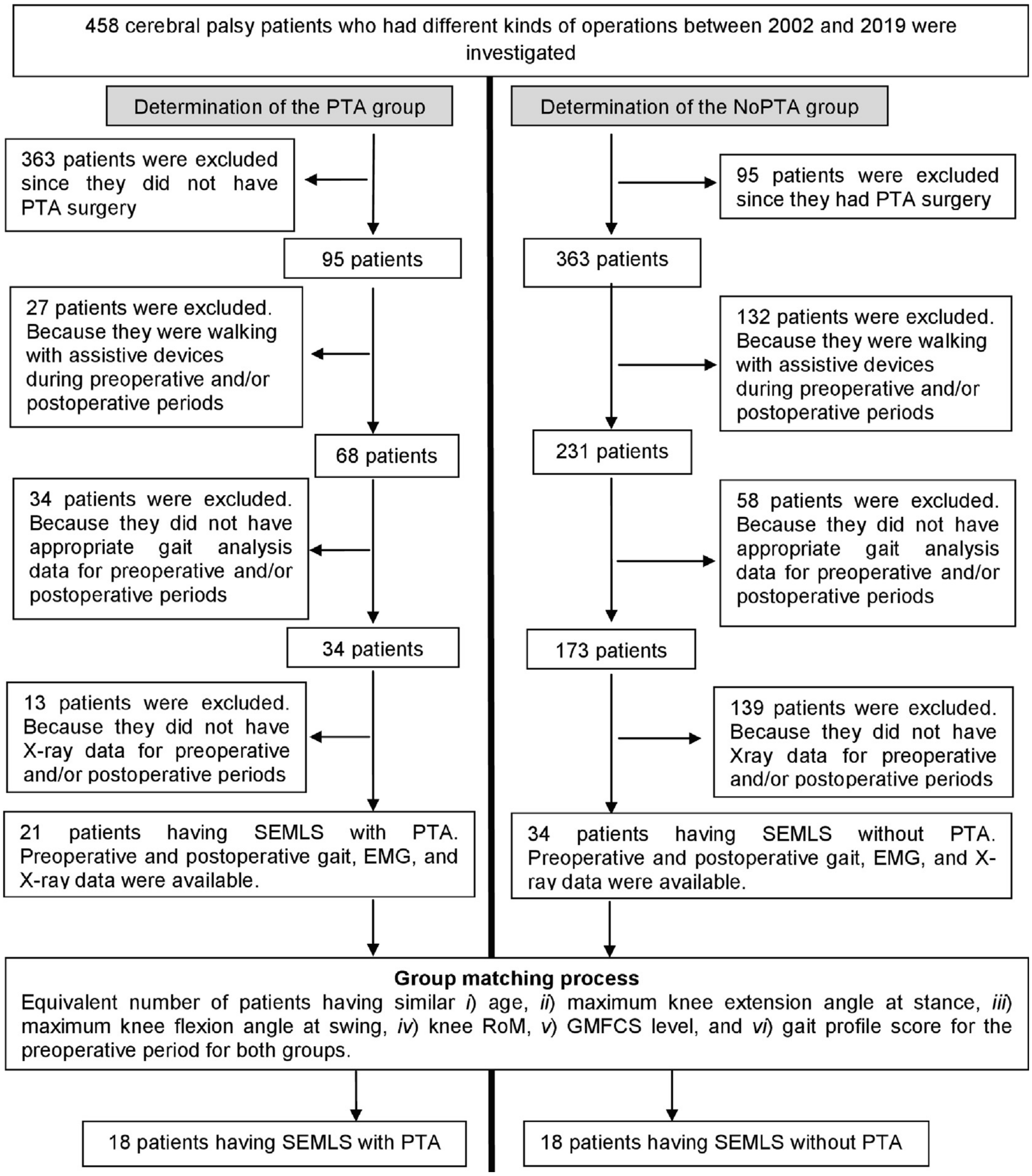

Figure 1. Flow-chart of patients. The patellar tendon advancement (PTA) group: cerebral palsy (CP) patients having single-event multilevel surgery (SEMLS) and PTA. The NoPTA group: CP patients having SEMLS without PTA. EMG, electromyography; GMFCS, Gross Motor Function Classification System; RoM, range of motion.

terthur, Switzerland). According to clinical standards, X-ray measurements were performed before and after surgery in lateral and medial projection at a knee flexion angle around 30°. Additionally, gait data of 18 healthy children (age 13.9 ± 1.3) were used for reference.

2.3. Musculoskeletal modeling

In order to quantify patella position, X-ray data could be used [10,17]. However, because the patients showed variable hip and knee joint angles during preoperative and postoperative X-ray measurements – a finding which is typical for a clinically oriented study – patella positions obtained from X-ray data may not be comparable between exams. Therefore, we used musculoskeletal modeling and simulation tools available in OpenSim software [25] with subject-specific representations for obtaining patella positions, knee joint angles, and knee extension moment arms (KEMA).

Table 1
Preoperative parameters and performed surgeries for the patellar tendon advancement (PTA) and without patellar tendon advancement (NoPTA) groups.

Preoperative parameters (mean ± SD)	PTA group (SEMLS with PTA)	NoPTA group (SEMLS without PTA)
Age	14.2 ± 2.6	14.3 ± 4.1
Maximum knee extension at stance	26.6 ± 13.7	25.7 ± 12.0
Maximum knee flexion at swing	57.3 ± 9.8	55.3 ± 9.8
Knee range of motion	26.5 ± 14.4	30.0 ± 8.2
GMFCS level	1.7 ± 0.6	1.9 ± 0.5
Gait profile score	13.8 ± 3.2	14.2 ± 3.2
Surgical procedures		
Extension osteotomy	12 patients/21 limbs	10 patients/14 limbs
Hamstring lengthening	7 patients/12 limbs	6 patients/9 limbs
Rectus femoris transfer	4 patients/8 limbs	5 patients/10 limbs
Derotation osteotomy	18 patients/30 limbs	18 patients/29 limbs

GMFCS, Gross Motor Function Classification System; SD, standard deviation; SEMLS, single-event multilevel surgery.

Rajagopal's full-body musculoskeletal model consisting of 22 segments and 80 Hill-type muscle–tendon units was used [26]. First, the generic musculoskeletal model was scaled to match the anthropometry of each patient. Then, the hip and knee joint angles of each patient's subject-specific musculoskeletal model in the sagittal plane were matched to those measured in the X-ray images. The location of the patella for the preoperative and postoperative cases was also adjusted considering the X-ray images. Further, the paths of the muscles were altered using via points, which are utilized to specify the muscle path between the origins and insertions of muscles in OpenSim.

The hip and knee joints of the models were set at 0° and 30°, respectively, to quantify patella position in a standard pose using the patellar height and IS ratio (Figure 2). The patellar height was measured as the distance between the tibial tuberosity and the patella inferior pole with the help of the customized model before and after surgery (Figure 2(a)) and the difference was calculated. The IS ratio was calculated accordingly (Figure 2(b)). An IS ratio between 0.8 and 1.2 was considered normal [17]. The KEMA was estimated as the peak value of the rectus femoris, vastus medialis, vastus lateralis, and vastus intermedius moment arms with respect to knee joint angle before and after surgery. Inverse kinematics was performed to calculate joint angles.

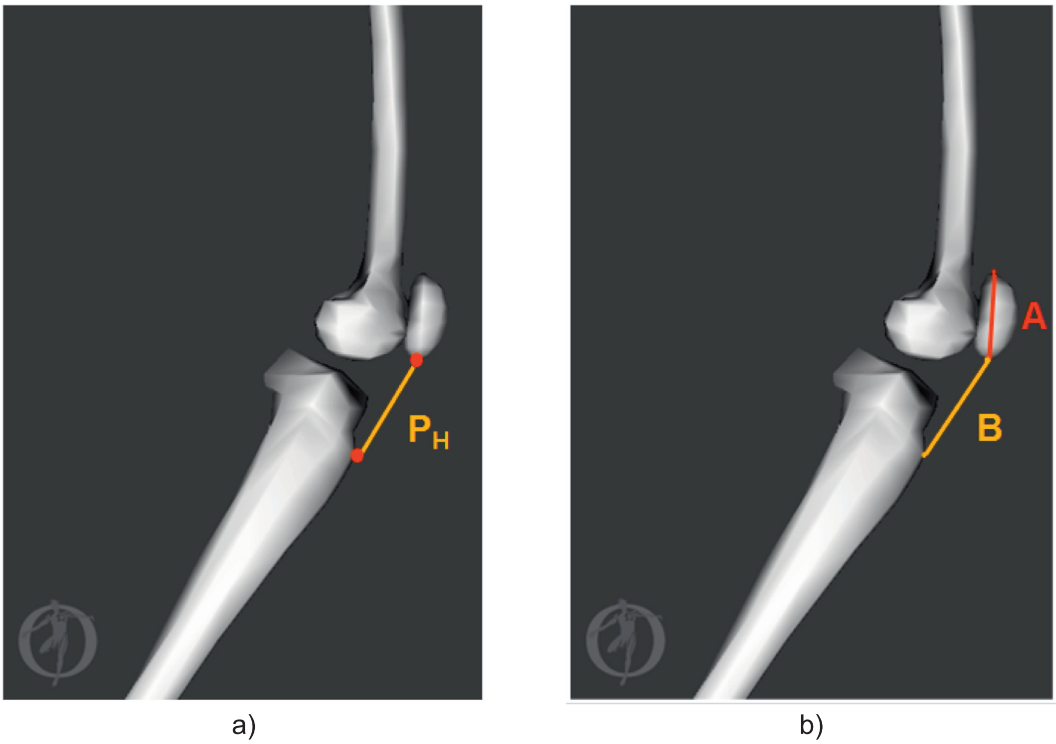

Figure 2. Determination of (a) patellar height (P_H) and (b) Insall-Salvati (IS) ratio. A: maximum length of the patella; B: length of the patellar tendon. IS ratio is calculated as B/A.

Table 2
Patellar height and Insall-Salvati (IS) ratio for the patellar tendon advancement (PTA) group obtained from the OpenSim model and X-ray data.

		Preop		Postop		Preop patellar height (mm)		Postop patellar height (mm)		Difference in patellar height (mm)		Preop IS ratio		Postop IS ratio	
Patients	Side (R/L)	Hip joint angle	Knee joint angle	Hip joint angle	Knee joint angle	OpenSim Model	X-ray data	OpenSim Model	X-ray data	OpenSim Model	X-ray data	OpenSim Model	X-ray data	OpenSim Model	X-ray data
P1	L	10.8	12.5	1.5	70.6	48.2	50.2	52.8	54.3	−4.6	−4.2	1.08	1.12	1.16	1.19
P2	L	0.3	32.4	0.6	31.5	63.0	64.3	58.1	59.8	4.9	4.5	1.16	1.19	1.04	1.06
P3	R	0.3	34.7	0.3	34.9	53.4	54.5	46.4	47.8	7.0	6.8	1.19	1.22	1.00	1.02
P4	R	21.8	35.9	8.7	31.7	55.7	57.4	52.9	54.5	2.8	2.9	1.20	1.23	1.11	1.13
P5	R	17.8	61.8	0.5	52.5	66.7	68.8	44.5	45.8	22.2	22.9	1.34	1.38	0.88	0.90
	L	0.4	29.8	15.1	66.4	42.9	44.3	42.9	44.2	0.1	0.1	0.86	0.89	0.84	0.86
P6	L	27.2	24.3	28.3	65.5	46.1	48.0	44.2	45.6	1.8	2.4	0.98	1.01	0.91	0.93
P7	R	29.1	31.3	12.2	45.1	51.9	52.5	42.0	43.2	9.9	9.2	1.06	1.09	0.83	0.85
	L	30.2	25.8	10.3	20.6	57.7	59.5	34.5	35.5	23.2	23.9	1.16	1.20	0.69	0.70
P8	R	25.7	1.1	1.7	1.2	45.7	47.1	30.4	31.3	15.3	15.8	1.16	1.19	0.75	0.76
	L	39.7	0.9	0.5	0.4	48.2	50.2	28.8	29.7	19.4	20.5	1.21	1.25	0.70	0.72
P9	R	16.5	45.1	1.8	41.7	49.6	51.7	44.6	45.9	5.0	5.7	1.06	1.09	0.92	0.94
	L	1.1	52.8	34.4	0.7	64.7	66.0	48.1	49.6	16.5	16.5	1.39	1.43	1.01	1.03
P10	R	0.5	63.5	0.8	38.4	60.4	61.7	50.5	52.0	10.0	9.7	1.30	1.34	1.07	1.09
P11	R	7.4	35.1	26.2	24.5	50.8	52.4	41.4	42.6	9.4	9.7	1.16	1.20	0.92	0.94
P12	R	24.1	11.7	20.3	7.7	60.2	61.5	41.7	42.9	18.5	18.5	1.31	1.35	0.89	0.90
	L	25.4	15.2	25.1	15.1	61.9	63.2	42.8	44.0	19.2	19.2	1.36	1.40	0.91	0.93
P13	R	23.8	12.6	0.3	25.3	44.1	45.0	33.9	34.9	10.2	10.1	1.16	1.20	0.87	0.89
	L	35.1	0.5	0.4	61.1	45.4	47.2	42.1	43.4	3.2	3.8	1.21	1.25	1.08	1.10
P14	R	43.7	0.8	14.3	23.6	36.9	38.0	40.4	41.6	−3.5	−3.6	0.74	0.76	0.80	0.82
	L	31.6	0.7	9.4	45.1	51.2	52.2	37.9	39.1	13.2	13.1	1.01	1.05	0.74	0.75
P15	R	1.2	1.9	15.5	16.4	66.4	67.8	54.3	56.0	12.1	11.8	1.45	1.49	1.16	1.18
	L	0.5	0.07	8.7	0.2	57.6	58.8	34.6	35.6	23.0	23.2	1.25	1.29	0.73	0.75
S16	R	6.8	35.2	17.1	16.8	43.1	44.0	34.7	35.8	8.3	8.2	0.98	1.01	0.75	0.77
	L	3.2	24.1	6.9	0.9	48.8	50.3	29.5	30.3	19.4	20.0	1.10	1.14	0.65	0.66
P17	R	5.3	18.8	20.1	16.6	56.4	58.7	48.5	50.0	7.9	8.8	1.34	1.38	1.12	1.14
	L	19.1	5.5	13.5	20.1	50.4	52.5	40.9	42.2	9.5	10.3	1.19	1.22	0.94	0.96
P18	R	36.9	10.6	19.5	21.1	61.9	64.4	45.9	47.3	15.9	17.1	1.25	1.29	0.90	0.92
	L	22.2	17.2	21.2	24.4	55.9	58.2	49.7	51.2	6.2	7.0	1.13	1.17	1.02	1.04

L, left; Postop, postoperative; Preop, preoperative; R, right.

To validate the accuracy of the patellar height measurements via musculoskeletal modeling, the values of patellar height and IS ratio obtained from X-ray images and models were compared. To do so, the hip and knee joint angles in each musculoskeletal model were adapted to the hip and knee posture in the corresponding X-ray images (Tables 2 and 3). There was no significant difference between the patellar height and IS ratio measurements obtained from the musculoskeletal model and X-ray images ($P > 0.05$).

2.4. Data analysis

Statistical analysis was performed using SPSS software (Version 21.0; SPSS; Chicago, IL, USA). The level of significance was set at 0.05. Normality of all variables (age, maximum knee extension at stance, maximum knee flexion at swing, RoM, GMFCS, gait profile scores, patellar height, IS ratio, KEMA) was disconfirmed using the Shapiro–Wilk test. Intra-comparisons for the dependent parameters (comparison of each group's preoperative and postoperative parameters) and inter-comparisons for the independent parameters (comparison of the groups with each other and normative data) were performed. Preoperative and postoperative results of each group were statistically analyzed using the one-way repeated-measures analysis of variance (ANOVA). The Kruskal–Wallis test was used for the statistical comparison of the PTA group, NoPTA group, and normative data. The Mann–Whitney *U*-test was employed to determine the significant difference between the groups. Bonferroni correction was applied to adjust the *P*-value for multiple comparisons ($P < 0.016$).

3. Results

The mean difference in patellar height pre- and postoperatively was found to be 10.8 ± 6.2 mm for the PTA group and 3.1 ± 4.1 mm for the NoPTA group ($P = 0.008$) (Table 4). Before surgery, there was a significant difference between the two groups in IS ratio ($P = 0.009$), but no difference postoperatively ($P > 0.016$). The IS ratio of the PTA group decreased from 1.2 ± 0.2 to 0.9 ± 0.1 postoperatively ($P = 0.009$). The IS ratio of the NoPTA group decreased from 1.0 ± 0.1 to 0.9 ± 0.1 postoperatively, but this was not statistically significant ($P > 0.05$). The mean change in patellar height was found to be 12.7 ± 5.

Table 3
Patellar height and Insall-Salvati (IS) ratio for the without patellar tendon advancement (NoPTA) group obtained from the OpenSim model and X-ray data.

		Preop		Postop		Preop patellar height (mm)		Postop patellar height (mm)		Difference in patellar height (mm)		Preop IS ratio		Postop IS ratio	
Patients	Side (R/L)	Hip joint angle	Knee joint angle	Hip joint angle	Knee joint angle	OpenSim Model	X-ray data	OpenSim Model	X-ray data	OpenSim Model	X-ray data	OpenSim Model	X-ray data	OpenSim Model	X-ray data
P1	R	9.3	49.2	3.8	15.4	47.5	49.2	53.4	54.1	−5.9	−4.9	0.89	0.92	0.99	1.00
P2	R	10.7	1.9	1.2	56.1	42.2	41.3	40.8	39.2	1.4	2.1	0.77	0.75	0.73	0.72
P3	R	9.5	40.1	0.3	48.4	56.7	55.9	50.2	51.2	6.6	4.7	1.07	1.06	0.94	0.96
	L	49.1	0.2	0.2	56.5	52.4	53.5	48.9	50.5	3.5	2.9	0.99	1.01	0.92	0.95
P4	R	41.4	0.3	34.4	0.2	43.7	45.2	39.5	40.4	4.2	4.8	0.95	0.98	0.84	0.86
	L	38.7	39.2	28.6	0.3	47.1	49.3	42.4	43.2	4.7	6.1	1.01	1.04	0.89	0.92
P5	R	34.6	25.8	14.5	0.2	58.1	56.4	46.5	44.3	11.5	12.1	1.08	1.05	0.86	0.83
	L	11.2	22.7	10.8	0.1	41.5	42.6	36.9	35.7	4.6	6.8	0.94	0.96	0.82	0.80
P6	L	62.1	0.2	41.1	0.3	43.5	45.7	37.2	39.9	6.3	5.7	1.05	1.07	0.88	0.92
P7	R	18.5	28.1	14.1	47.3	50.7	49.6	45.8	47.6	4.9	2.0	0.98	0.96	0.88	0.91
	L	40.4	0.5	0.2	0.3	39.6	40.2	36.8	38.8	2.8	1.4	0.95	0.96	0.87	0.89
P8	R	0.2	45.1	13.9	43.2	35.2	34.4	41.0	39.6	−5.8	−5.22	0.84	0.82	0.97	0.94
	L	0.5	70.3	0.4	53.2	44.1	43.8	39.7	37.9	4.4	5.8	1.03	1.02	0.92	0.88
P9	L	0.5	32.8	0.2	45.2	48.5	50.8	42.9	43.6	5.7	7.2	1.12	1.18	0.98	1.00
P10	L	11.2	0.1	0.2	33.3	42.7	41.9	35.3	33.4	7.4	8.5	0.97	0.95	0.8	0.76
P11	L	23.4	51.1	14.4	92.2	44.8	42.9	41.2	40.4	3.6	2.6	0.96	0.92	0.87	0.86
P12	R	14.8	1.2	0.2	80.3	37.4	38.9	40.8	42.6	−3.4	−3.7	0.81	0.84	0.87	0.90
	L	0.1	2.7	0.1	105	44.8	45.8	50.1	52.4	−5.2	−6.6	0.96	0.98	1.06	1.11
P13	L	14.5	43.4	6.2	45.1	44.96	46.5	41.4	42.7	3.6	3.8	0.81	0.82	0.79	0.81
P14	R	2.8	11.9	0.2	46.3	40.7	43.6	35.9	37.3	4.8	6.2	0.81	0.83	0.80	0.81
	L	22.7	0.5	1.4	41.3	60.4	62.7	55.7	54.3	4.8	8.4	1.19	1.22	1.08	1.05
P15	R	85.7	2.8	32.9	10.8	57.7	59.9	54.9	57.6	2.8	2.3	1.11	1.15	1.04	1.09
S16	R	39.3	20.6	2.7	51.6	44.9	42.3	40.4	39.3	4.6	3.0	0.95	0.90	0.84	0.82
P17	R	2.3	1.5	1.2	82.7	48.1	49.3	44.5	46.4	3.6	2.9	0.96	0.97	0.89	0.92
P18	R	60.6	6.9	2.3	78.1	58.2	59.8	55.8	57.9	2.5	1.8	1.13	1.16	1.07	1.11
	L	27.7	1.5	1.7	70.4	55.3	57.9	51.4	53.8	3.9	4.2	1.06	1.08	0.97	0.99

L, left; Postop, postoperative; Preop, preoperative; R, right.

Table 4
Mean patellar heights and Insall-Salvati (IS) ratios for the patellar tendon advancement (PTA) and without patellar tendon advancement (NoPTA) groups.

		Preop patellar height (mm)	Postop patellar height (mm)	Difference in patellar height (mm)	Preop IS ratio	Postop IS ratio
PTA group	Bony	55.0 ± 7.6	42.3 ± 7.4	12.7 ± 5.9	1.2 ± 0.2	0.9 ± 0.1
	Soft tissue	52.1 ± 6.1	43.6 ± 5.9	8.2 ± 5.8	1.1 ± 0.2	0.9 ± 0.2
	Mean	53.8 ± 7.0	43.0 ± 6.8	10.8 ± 6.2	1.2 ± 0.2	0.9 ± 0.1
NoPTA group		47.3 ± 6.9	44.2 ± 6.4	3.1 ± 4.1	1.0 ± 0.1	0.9 ± 0.1

P-value	Patellar height	Difference	IS ratio
Preop PTA group vs. preop NoPTA group	**0.01**	–	**0.009**
Postop PTA group vs. postop NoPTA group	0.107	–	0.351
Preop PTA group vs. postop PTA group	**0.004**	–	**0.009**
Preop NoPTA group vs. postop NoPTA group	0.051	–	0.182
PTA group vs. NoPTA group	–	**0.008**	–
Bony procedure preop vs. soft tissue procedure preop	0.055	–	**0.014**
Bony procedure postop vs. soft tissue procedure postop	0.452	–	0.151
Bony procedure preop vs. bony procedure postop	**0.005**	–	**0.007**
Soft tissue procedure preop vs. soft tissue procedure postop	**0.007**	–	–
Bony procedure vs. soft tissue procedure	–	**0.012**	–

Significant differences are shown in bold. The missing values (–) indicate that no statistical analysis was performed for the corresponding pair. Postop, postoperative; Preop, preoperative.

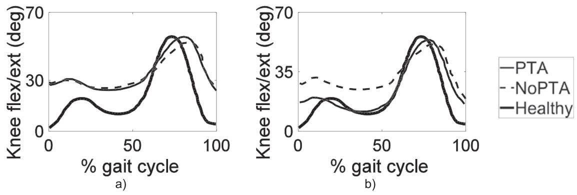

Figure 3. Mean knee joint flexion/extension angle over a gait cycle for (a) preoperative and, (b) postoperative periods. Gray zone indicates normative data obtained from the age-matched healthy reference group. NoPTA, without patellar tendon advancement; PTA, patellar tendon advancement.

Table 5
Mean knee joint angle, range of motion (RoM), and peak knee extension moment arm (KEMA) of the patellar tendon advancement (PTA) and without patellar tendon advancement (NoPTA) groups.

	Maximum knee extension angle (at stance)	Maximum knee flexion angle (at swing)	RoM	KEMA (cm)	
Preop	PTA group	26.6 ± 13.7	57.3 ± 9.8	26.5 ± 14.4	4.0 ± 0.5
	NoPTA group	25.7 ± 12.0	55.3 ± 9.8	30.0 ± 8.2	4.5 ± 0.6
Postop	PTA group	11.1 ± 12.6	54.7 ± 12.3	43.6 ± 14.2	4.6 ± 0.5
	NoPTA group	24.8 ± 20.8	52.9 ± 18.5	32.1 ± 13.3	4.6 ± 0.5
	Normal*	10.2 ± 4.0	59.0 ± 4.9	49.8 ± 5.3	4.8 ± 0.3
		P-value			
PTA vs. NoPTA group	Preop	0.425	0.371	0.289	**0.009**
	Postop	**0.012**	0.343	**0.012**	0.876
Preop vs. postop	PTA group	**0.012**	0.256	**0.009**	**0.008**
	NoPTA group	0.417	0.245	0.368	0.201
Normative vs.	PTA group-preop	**0.009**	0.342	**0.007**	**0.006**
	PTA group-postop	0.382	0.207	**0.015**	**0.014**
	NoPTA group-preop	**0.011**	0.225	**0.009**	**0.013**
	NoPTA group-postop	**0.011**	**0.014**	**0.011**	**0.015**

*Normative data obtained from the age-matched healthy group. Significant differences are shown in bold. Postop, postoperative; Preop, preoperative.

9 mm for the bony procedure and 8.2 ± 5.8 mm for the soft tissue procedure ($P = 0.012$). IS ratio reduced from 1.2 ± 0.2 to 0.9 ± 0.1 for the bony procedure ($P = 0.007$) and from 1.1 ± 0.2 to 0.9 ± 0.2 for the soft tissue procedure ($P = 0.011$). While there was a significant difference between the preoperative IS ratios of the two procedures ($P = 0.014$), no difference was found postoperatively ($P > 0.016$).

The PTA and NoPTA groups showed similar knee joint angle patterns preoperatively (Figure 3(a)). Postoperatively, the PTA group was closer to the reference group than the NoPTA group, especially at initial contact (Figure 3(b)). Both groups showed a reduced and delayed peak knee flexion postoperatively (Figure 3(a), (b)).

Maximum knee extension at stance, maximum knee flexion at swing, RoM, and peak KEMA of both groups were given in Table 5. There was no significant difference between groups preoperatively in terms of peak knee flexion and RoM, but there was a statistical difference in maximum knee extension ($P = 0.012$) and RoM ($P = 0.012$) postoperatively. Maximum knee extension significantly decreased in the PTA group postoperatively ($P = 0.012$), but did not change for the NoPTA group ($P > 0.05$). There was no significant difference between maximum knee flexion in either group when compared with normative data preoperatively ($P > 0.016$). RoM increased significantly for the PTA group ($P = 0.009$), while it did not differ for the NoPTA group postoperatively ($P > 0.05$). Both groups differed significantly from the healthy group preoperatively in terms of maximum knee extension and RoM ($P < 0.016$). There was no significant difference ($P > 0.016$) between the healthy and PTA groups postoperatively (Table 5), while the NoPTA group continued to show a significant difference compared with normative data after surgery ($P < 0.016$).

For the peak KEMA, there was a significant increase in the PTA group from 4.0 ± 0.5 cm to 4.6 ± 0.5 cm (rate of change: 15.44%) postoperatively ($P = 0.008$). No postoperative difference was found in the NoPTA group (rate of change: 2.67%) ($P > 0.05$). Before surgery, there was a statistical difference between the two groups ($P = 0.009$), but no difference was observed postoperatively ($P > 0.016$). Both groups significantly differed from the healthy group before and after surgery ($P < 0.016$).

4. Discussion

Quantification of patella position pre- and postoperatively is crucial for interpreting the effect of surgeries addressing knee function in patients with CP. However, in the literature, there is no validated method for the objective determination of the patellar height. The measurement of IS ratio from X-ray image may be biased because it highly depends on the knee joint angle which may vary between pre- and postoperative X-ray examinations [20–22]. Therefore, we used a musculoskeletal model to obtain more accurate and unbiased patellar height values. Because there was no significant difference between patella positions obtained from X-ray data and musculoskeletal modeling (Tables 2 and 3), the determination of patellar height through the modeling was found to be an objective procedure. The method we have proposed in this study enables users to adapt the generic model to be the same as an X-ray image of a patient to quantify the patellar height at specific hip and knee joint angles.

The pre- and postoperative patella positions were evaluated by using patellar height and IS ratio. There was no difference between exams in terms of patellar height and IS ratio in the NoPTA group which served as a reference whereas PTA significantly altered the patellar height (Table 4). The positive effect of PTA was also observed in IS ratio. This finding confirms earlier work by Sossai et al., who investigated the patients subjected to PTA with additional surgeries and found improvement in patellar height with respect to the Koshino Index [9].

Patella alta is typically found in children with CP and crouch gait [1,4–6]. Besides patella alta, there are several causes for the development of crouch gait such as hamstring tightness, lever-arm dysfunction, and impaired balance [4,6]. Therefore it may seem beneficial to perform PTA as a prophylactic procedure in addition to hamstring lengthening or femoral extension osteotomy in patients with crouch gait even when they have no patella alta. However, in our center, we found that most of the patients who received PTA were also diagnosed with patella alta; and, vice versa, in cases showing crouch but no patella alta, no PTA had been performed. Our finding here is that the NoPTA group still had a crouch gait pattern postoperatively.

Two different PTA procedures were evaluated in our research. We found a significantly larger effect on patellar height and IS ratio by the bony procedure (Table 4). This finding is consistent with Seidl et al. who compared three different surgical techniques using human cadaveric knees and reported that the bony procedure resulted in a substantial difference in patellar height postoperatively [6].

We also investigated the relationship between patella position, knee joint kinematics, and KEMA in the context of PTA in combination with SEMLS. We found that knee extension angles at stance and initial contact reduced in the PTA group, while there was no significant difference in the NoPTA group postoperatively (Figure 3). Other researchers also reported similar outcomes after PTA. Sossai et al. revealed that PTA corrected the flexed knee gait by 20° during the gait cycle [9]. But the limitation of that study was that they included only patients subjected to PTA which caused the lack of comparison with the NoPTA group. Klotz et al. compared the PTA and NoPTA groups [14]. They reported that PTA had an advantage for the recovery of the crouch gait. Their findings were not statistically different because of the limited sample size. They also found that PTA may cause stiff knee gait postoperatively. Goldberg et al. defined four parameters for the establishment of stiff knee gait [27]; two of them are reduced and delayed knee flexion in swing phase [28,29]. In our study, maximum knee flexion at swing decreased for both groups. But only the NoPTA group showed the statistical difference when compared with healthy subjects (Table 5). For the PTA and NoPTA groups, there was a time delay to achieve maximum knee flexion preoperatively, but it reduced for both groups postoperatively.

Patella alta is also associated with knee extension lag in patients with CP [5,13]. PTA is therefore performed to enhance KEMA by changing patellar height. Ward et al. reported that there was no difference between KEMA of adults with and without patella alta [30]. Bittmann et al. retrospectively analyzed preoperative and postoperative radiographs and gait metrics of patients who had distal femoral extension osteotomy and PTA surgeries [10]. They found that the advancement of the patella enhanced the KEMA which may contribute to the treatment of crouch gait. In our study, we also examined the effect of PTA on the KEMA. The PTA group, in contrast to the NoPTA group, had substantial improvement in KEMA postoperatively. Our results showed that PTA enhanced the KEMA significantly, which may contribute to the more extended knee postoperatively. Similarly, there was no significant decrease in knee flexion of the NoPTA group which also did not show an increase in KEMA. This result supports the judgment that PTA should be performed for improving knee extension in gait independently of the patellar height, as reported by Das et al. and Stout et al. [4,12]. However, any additional surgery may have risks and be a potential source of pain which has to be balanced with potential functional benefits.

Limitations of this study should be considered. First, the generic full-body musculoskeletal model [26] was used without introducing the skeletal deformities of the patients, except for patella alta. Patients in both groups had undergone several concomitant surgeries. PTA was explicitly introduced in the model but no other CP-specific pathologies were individually taken into account in the modeling step – a reason why concomitant surgeries were addresses in the matching process. Therefore, particularly rigorous matching was used to keep the bias small which may stem from structural differences between groups. Second, the groups included only a limited number of patients due to the rather rigorous process for an equal group match including also the surgical program next to PTA. However, the slightly higher number of surgeries specifically addressing the knee function (Table 1) in the PTA group may form a bias for overestimating the effect of PTA. Nevertheless, there was no statistical difference between the groups in terms of preoperative characteristics. Third, X-ray data were available only for the sagittal plane. Therefore, positioning of the patella along the mediolateral axis was not possible in musculoskeletal modeling. Fourth, due to ethical concerns, X-ray data were not available for the healthy group. We assumed that the healthy group had a normal patella position which could be represented by the scaled-generic musculoskeletal model. This assumption may lead to errors in calculating the biomechanical parameters of the healthy group. Finally, we monitored only short-term results. Boyer et al. pointed out that significant changes in knee extension and knee flexion at stance phase may appear at long-term follow up [11].

5. Conclusions

Musculoskeletal modeling is an effective tool for the accurate determination of the patellar height. The bony procedure for PTA provides a better postoperative IS ratio than the soft tissue procedure. PTA improves the patella position and knee extension moment arm, and is an effective procedure for improving knee extension of patients with CP and crouch gait. Long-term follow up measurements should be examined for assessing the endurance of this improvement.

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Declaration of Competing Interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.knee.2021.07.010.

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