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Predicting the outcome of intramuscular psoas lengthening in children with cerebral palsy using preoperative gait data and the random forest algorithm

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ABSTRACT

This study used the random forest algorithm to predict outcomes of intramuscular psoas lengthening as part of a single event multi-level surgery in patients with cerebral palsy. Data related to preoperative medical history, physical exam, and instrumented three-dimensional gait analysis were extracted from a historic database in a motion analysis center. Data from 800 limbs of patients with diplegic cerebral palsy were analyzed. An index quantifying the overall deviation in pelvic tilt and hip flexion was used to define outcome categories. The random forest algorithm was used to derive criteria that predicted the outcome of a limb. The criteria were applied to limbs that underwent psoas lengthening with outstanding results (accuracy = .78, sensitivity = .82, specificity = .73). The criteria were then validated using an extended retrospective case–control design. Case limbs met the criteria and underwent psoas lengthening. Control limbs met the criteria, but did not undergo psoas lengthening. Over-treated limbs failed the criteria and underwent psoas lengthening. Other-treated limbs failed the criteria and did not undergo psoas lengthening. The rate of good outcomes among Cases exceeded that observed among controls (82% vs. 60%, relative risk = 1.37), and far exceeded that observed in Over-treated limbs (27%). Other-treated limbs had good outcomes 52% of the time. Application of the criteria in the future is estimated to increase the overall rate of good pelvis–hip outcomes from 58% to 72% among children with diplegia who undergo single-event multi-level surgery (SEMLS).

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1. Introduction

1.1. Hip flexion contracture and psoas lengthening surgery

The hip flexors provide propulsion in normal gait, and are important to many activities of daily living and independent mobility. Hip flexion contractures are a common problem in cerebral palsy (CP), often leading to dynamic impairments in gait and functional activities. The source of hip flexion contractures in CP is often the multi-joint Psoas, owing to the magnitude of the muscle's hip flexion moment arm, and the predominance of multi-joint muscle problems in CP [1]. Hip flexion contractures are commonly identified using the Thomas test. However, reliance on the Thomas test for surgical decision-making is problematic since the test has marginal reliability and validity, and has not been shown to be predictive of outcomes [2].

A common treatment for hip flexion contracture in CP is the intramuscular psoas lengthening over the pelvic brim [3–8]. This treatment remains controversial for several reasons including concerns over iatrogenic weakening of the hip flexors and safety due to the proximity of the femoral nerve and artery [3,9–11]. However, several recent outcome studies have documented subjects undergoing the surgery without femoral nerve or artery damage as a complication [4–6]. Part of the controversy related to psoas lengthening stems from a lack of studies describing both specific indications for the operation, and results showing efficacy of surgical treatment compared to matched controls. In one of the most commonly cited studies, Sutherland et al. showed generally positive outcomes. However, the use of an assistive device and advancing age appeared to be contraindications [3]. Patient selection criteria were not described in that study. Instead, a single case-study was discussed, presumably as a prototype for the ideal surgical candidate. This subject presented with symptoms common to ambulatory CP: increased pelvic tilt, hip and knee flexion, as well as excessive activity of the rectus femoris, hamstrings, adductors, and iliacus. The study did not include a comparison or control group, and hence it was unclear whether the psoas-lengthening was responsible for the observed improvements, or these could have resulted from the multiple concomitant operations.

Novacheck et al. examined pelvis and hip specific outcomes for subjects undergoing psoas lengthening, and a comparison group undergoing multi-level surgery that did not include psoas lengthening [4]. The psoas lengthening group exhibited

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significantly improved hip flexion contracture by physical exam, and better outcomes with respect to overall hip flexor function, maximum pelvic tilt, pelvic tilt range of motion, and hip extension in stance. However, the comparison group was not well matched in terms of amount of preoperative hip flexion contracture and concomitant hamstrings lengthening. Furthermore, no specific criteria were proposed for choosing limbs likely to benefit from psoas lengthening.

Morais et al. were the first to propose a general set of criteria for patient selection [6]. The authors evaluated pelvic and hip outcomes following psoas lengthening on 52 sides from 26 patients, and proposed that limbs exhibiting one-out-of-three among: (1) increased pelvic tilt, (2) increased pelvic tilt range of motion, or (3) lack of hip extension in terminal stance were appropriate for psoas lengthening. However, specific levels of the three variables were not stated. Furthermore, the outcomes of Morais' study were mixed. While pelvic tilt range of motion improved, reduction of anterior pelvic tilt was only seen in patients who were GMFCS levels I and II. The cohort, as a whole, did not show a significant improvement in hip extension in gait. Lastly, the study included neither a control nor a comparison group. Thus observed improvements could not be unambiguously attributed to psoas lengthening.

Truong proposed explicit criteria for psoas lengthening as part of a single-event multi-level surgery (SEMLS) [5]. These criteria stated that a limb must be more than two standard deviations away from normal for two-out-of-three of the following variables: (1) pelvic tilt, (2) pelvic tilt range-of-motion, and (3) hip extension in stance. Truong's study included a matched control group comprised of limbs that met the two-out-of-three criteria, but did not receive psoas lengthening. Based on these criteria, 32 case limbs (met criteria +Psoas) and 55 control limbs (met criteria −Psoas) were identified. The criteria led to good results overall, but did not show clear advantages for the cases compared to the controls.

It is apparent that clear and explicit guidance for psoas lengthening is sorely lacking. Ideally, criteria would fulfill three pre-requisites: (1) criteria would be explicit and not rely on vague or subjective descriptions, (2) criteria would be predictive of outcomes among limbs undergoing psoas lengthening, and (3) criteria would be pertain specifically to psoas lengthening.

1.2. The random forest algorithm for predicting outcome

The random forest (RF) algorithm is a powerful new statistical classifier that is used in many fields, but is relatively novel to orthopedic surgery and clinical gait analysis [12]. The RF algorithm predicts a *class* (good/poor outcome) for an *observation* (limb) based on a set of *predictor variables* (e.g. gait data, medical history, etc.). The RF algorithm is considered to be superior to most existing classifiers [12–14].

Briefly, the RF algorithm works as follows (see [12] for details)

1. Start with a set of observations (limbs) and associated predictor variables (gait data, physical exam, etc.).
2. Generate a large number of bootstrap replicate sets of observations from the original set of observations. Approximately 37% of the original observations are absent from any one bootstrap replicate. These are called "out-of-bag" observations.
3. Construct a classification tree for each bootstrap replicate [15]. At each node of each tree, choose classification rules (splits) from a small random subset of all possible predictor variables.
4. Evaluate each observation using all trees for which that observation is in the out-of-bag set. This produces an independent estimate of the classification error rate. The approach is similar to the use of separate training and test sets, or to *N*-fold cross validation.
5. The overall predicted class of an observation is determined by the fraction of votes for a given class.

In addition to predicting the class of an observation, the RF algorithm estimates the predictive importance of individual variables [12]. The importance is the percent by which the classification accuracy decreases after a variable is randomly permuted among the observations. Using a small number ofthe most important variables can often produce a superior classifier.

The goals of this study were: (1) to predict the outcome of psoas lengthening as part of a SEMLS using a set of preoperative predictor variables, and (2) show that the criteria pertain specifically to psoas lengthening.

2. Materials and methods

2.1. Selection of limbs

The database of the motion analysis center was queried to identify limbs for analysis. Limbs were included if they belonged to a subject with the diagnosis of CP, were treated with single event multi-level surgery (SEMLS – defined as more than one orthopedic operation other than removal of instrumentation), underwent preoperative gait analysis no more than 18 months prior to SEMLS, and underwent post-operative gait analysis between 9 and 36 months after SEMLS. There was no exclusion of limbs that had undergone prior treatment. Limbs were allocated into two groups depending on whether or not psoas lengthening was included as part of the SEMLS (+Psoas and −Psoas respectively).

2.2. Definition of classes

Outcome categories were defined using a pelvis–hip specific measure: the Pelvis–Hip Deviation Index (PHiDI) [5]. The PHiDI is a single number representing the deviations from normal of both pelvic tilt and hip flexion. The PHiDI is defined so

Table 1
Classifier performance.

		Met criteria	Failed criteria	Total
Confusion matrices				
+Psoas	Good outcome	102	23	125 good
	Poor outcome	23	62	85 poor
	Total	125 Cases	85 Over-Treated	210
		$\chi^2 = 62.5$, $p = 2.7e-15$		
−Psoas	Good outcome	250	89	339 good
	Poor outcome	170	81	251 poor
	Total	420 Controls	170 Other-Treated	590
		$\chi^2 = 2.5$, $p = .11$		

	Accuracy	Sensitivity	Specificity	AUC	Rel. risk	MCC
Classification metrics						
+Psoas	.78	.82	.73	.83	3.02	0.55
−Psoas	.56	.74	.32	.57	1.14	0.07

AUC: area under ROC curve; MCC: Matthews correlation coefficient.

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