PLEXBASE: A DIGITAL MODEL OF THE BRACHIAL PLEXUS

Jeffrey L. Sponsler, MD, MS
Alaska Brain Center, LLC
4551 E Bogard Rd Wasilla AK 99654
jsponsler@akbraincenter.com

ABSTRACT
The brachial plexus is a complex anatomic structure. No object oriented models of the plexus are described previously. The project goal was to develop an object oriented brachial plexus model. An object oriented model of the plexus called PLEXBASE has been created using Lisp. Interface functions were developed to query the knowledge base. Using logic programming and back-chaining rule-base, decision support rules to diagnose plexus disorders were developed. Development of plexus disorder benchmarks was done to exercise the rule-base. Testing of rules against benchmarks was completed. The sensitivity of each diagnostic rule set (for the corresponding benchmark) was 100%. The brachial plexus model and associated software is comprehensive and accurate for anatomic study and clinical analysis of this important structure.

KEY WORDS
Artificial Intelligence, Expert Systems, Lisp, Brachial Plexus

1. Introduction

The brachial plexus (BP) is a formed by anterior rami of spinal nerves C3 to T1 [1]. It is described as having three *trunks*, the superior trunk, middle trunk, and the inferior trunk. The next distal components are called *divisions*, anterior and posterior. Each division has a superior, middle, and inferior subdivision. The next distal components are termed *cords* (posterior, medial, and lateral cords). The final substructures are branches (nerves) and these include the musculocutaneous nerve, the axillary nerve, the median nerve, and the ulnar nerve. There are several smaller branches from the plexus.

The plexus includes sensory axons and motor axons. The motor axons carry action potentials from the ventral horn cells of the spinal cord to the neuromuscular junction of target muscles [2]. The sensory components of the brachial plexus are complex. The pseudo-unipolar neurons (in the dorsal root ganglia) project axons to the dorsal horn and to the corresponding dermatome via the brachial plexus. For example, the sensory C5 spinal ganglion projects to the dorsal horn of the spinal cord and sends axons to the C5 dermatome via different pathways: one pathway is the superior trunk, the anterior division, the lateral cord, and the musculocutaneous nerve. There is another pathway that includes the posterior cord and axillary nerve. For the model to be complete, all such connections have been described in the knowledge code. Sensory action potentials travel from cutaneous receptors to the spinal cord dorsal horn.

An Internet search finds no reports on computer models of the brachial plexus. Gonik [3] used a crash test computer model to analyze plexus stretching during parturition.

2. Methods and Materials

A knowledge based program called *PLEXBASE* has been designed and developed at the Alaska Brain Center and is described in this report.

The language Common Lisp [4], Common Lisp Object System (CLOS) [5], and the logic programming language Prolisp [6] were employed in this effort. Our efforts in the past have included coding a software atlas of the major components of the central nervous system. This system, the Neuro-Anatomic Atlas [7], includes major systems of the brain, spinal cord, and peripheral nervous system. An AI development toolkit, the NEUROBRIDGE [8] is the software infrastructure for research and development for neuroscience.

In this report, the organization of PLEXBASE is described. Functions for accessing the knowledge base are described. Prolisp has been used as a depth-first search engine to PLEXBASE. Diagnostic rules and results are described. These identifiers have been added to the BP anatomy: anterior-division-superior, anterior-division-middle, anterior-division-inferior, posterior-division-superior, posterior-division-middle, and posterior-division-inferior. These new names help to provide more detail in the path of axons through the plexus.

Rules for the medical diagnosis engine StrokeDx [8] were encoded to diagnose lesions in the plexus and these rules employ the knowledge in the PLEXBASE. StrokeDx [9] is coded in Prolisp and employs hypothesis driven depth-first search. StrokeDx includes rules to diagnose clinical disorders of the brachial plexus; the rules access the PLEXBASE network. StrokeDx rules for brachial plexus disorders are described below.

The PLEXBASE identifiers are defined for left and for right sides of the body. Muscle biceps-brachii-right is, for example, tagged with “-right”. In some examples, the left/right designations are not included.

Benchmark Cases

Benchmark data files were manually created to test the diagnostic system. Each benchmark encodes the typical motor and sensory findings for a brachial plexus lesion. For example, the superior trunk lesion will typically produce weakness in biceps and deltoid muscles and will cause sensory deficits in the C5 dermatome (lateral arm and thumb).

Utilization of logic programming tool PROLISP

In a previous medical AI experiment, a custom built *Prolog in Lisp* system called Prolisp was developed [9]. Prolisp uses CLOS classes to store rules and facts. Prolisp uses *facts*, *rules*, *unification*, and *resolution* in a manner similar to Prolog [10, 11]. Prolisp incorporates the *rewrite rule* [12] that links a rule to a Lisp function that performs an operation and returns its results to Prolisp. In all examples in this report, the Prolisp operator *proof* is called to initiate the deductive search through rules and facts. If the proof succeeds, variables are bound and these bindings represent the answer(s) to the query. The proof operator returns either :PROOF or :FAIL based on the query results. In examples below, the returned flag will not be shown. Prolisp variables are defined to begin with a question mark; for example *?nerve*. Knowledge structures in PLEXBASE are converted to Prolisp facts on which rule matching is applied.

3. Brachial Plexus Knowledge Base

Two classes, *motor-connection* and *sensory-connection*, are defined to support PLEXBASE.

A motor-connection transmits efferent signals from the spinal cord to a muscle and contains attributes as follows. The connection *source* is where the neuron cell body lies (e.g., ventral-horn-c5-right), *trunk* (superior-trunk-right), *division* (anterior-division-superior-right), *cord* (lateral-cord-right), *nerve* (musculocutaneous-nerve-right), and *destination* (biceps-brachii-right). For the motor connection between C5 and biceps, the following fact is generated:

```
(MOTOR-CONNECTION VENTRAL-HORN-C5-RIGHT
SUPERIOR-TRUNK-RIGHT ANTERIOR-DIVISION-SUPERIOR-
RIGHT LATERAL-CORD-RIGHT MUSCULOCUTANEOUS-
NERVE-RIGHT BICEPS-BRACHII-RIGHT)
```

The second key concept (and class) is the *sensory-connection*. A sensory-connection transmits afferent signals from a cutaneous receptor to the dorsal horn of the spinal cord. A sensory connection contains attributes as follows. The connection *source* is where the neuron cell body lies (e.g., spinal-ganglion-c5-right), *trunk* (superior-trunk-right), *division* (anterior-division-superior-right), *cord* (lateral-cord-right), *nerve* (musculocutaneous-nerve-right), and *destination* (dermatome-c5-right). The pseudo-unipolar neurons of the spinal ganglia project to the ipsilateral dorsal horn and through the ipsilateral brachial plexus [13].

All named structures of the plexus, peripheral nerves, muscles, spinal cord structures, and nerve roots are defined and instantiated as objects in the knowledge base and can then be accessed. The roots and ventral horn associate in a one-to-one relationship and so root identifiers are prefixed with “ventral-horn” in this application.

The system is designed to convert knowledge from PLEXBASE to Prolisp facts. Each object is converted to a Prolisp fact and stored as a Prolisp fact. PLEXBASE knowledge network can also be accessed by a library of Lisp functions. Prolisp rewrite-rules are used to access PLEXBASE knowledge; an example rewrite-rule *muscles-for-trunk ?trunk* obtains all muscles for a specific trunk.

4. PLEXBASE Query Rules

In this section, the library of rules to access and do elementary reasoning about the brachial plexus is described. In some examples, a query history ?hx variable is shown.

MOTOR-CONNECTION

Using the Prolisp proof operator, a search of the fact base for a motor-connection from spine to deltoid muscle can be done. The variable bindings yield knowledge of the plexus components of this connection.

```
(proof '(motor-connection ?root1 ?trunk1 ?division1 ?cord1
?nerve1 deltoid-right))
?ROOT1 = VENTRAL-HORN-C5-RIGHT
?TRUNK1 = SUPERIOR-TRUNK-RIGHT
?DIVISION1 = POSTERIOR-DIVISION-SUPERIOR-RIGHT
?CORD1 = POSTERIOR-CORD-RIGHT
?NERVE1 = AXILLARY-NERVE-RIGHT
```

To find the motor connection to the biceps:

```
(proof '(motor-connection ?root1 ?trunk1 ?division1 ?cord1
?nerve1 biceps-brachii-right))
?ROOT1 = VENTRAL-HORN-C5-RIGHT
?TRUNK1 = SUPERIOR-TRUNK-RIGHT
?DIVISION1 = ANTERIOR-DIVISION-SUPERIOR-RIGHT
?CORD1 = LATERAL-CORD-RIGHT
?NERVE1 = MUSCULOCUTANEOUS-NERVE-RIGHT
```

The proof variable bindings are displayed above. Note that the division, cord, and nerve are different for biceps and deltoid muscles.

HAS-SAME-ROOT (?muscle1 ?muscle2 ?root)

The *has-same-root* rule queries PLEXBASE, obtains roots for ?muscle1 and ?muscle2 and runs an intersection operator producing the ?root answer. If there are no common nerve roots, the proof will fail. Clinical relevance: An injury to a nerve root could produce weakness in the muscles sharing the root.

```
(proof '(has-same-root deltoid-right biceps-brachii-right ?root))
?ROOT = VENTRAL-HORN-C5-RIGHT
```

HAS-SAME-TRUNK (?muscle1 ?muscle2 ?trunk)

The *has-same-trunk* rule queries the BP knowledge base, obtains trunks for both muscles, applies intersection, and binds the result variable ?trunk. Clinical relevance:

Damage to the trunk could produce weakness in the two muscles.

(proof '(has-same-trunk deltoid-right biceps-brachii-right ?trunk))
?TRUNK = SUPERIOR-TRUNK-RIGHT

HAS-SAME-CORD (?muscle1 ?muscle2 ?cord)

This *has-same-cord* rule queries the BP knowledge base, obtains cords for both muscles, applies intersection, and binds the variable ?cord. In the example below, the first muscle name has been included in the proof pattern. Clinical relevance: damage to the cord can produce weakness in the two muscles sharing that cord.

(proof '(has-same-cord deltoid-right ?muscle2 ?cord))
?MUSCLE2 = SUPINATOR-RIGHT
?CORD = POSTERIOR-CORD-RIGHT

In this proof example, the two muscles do not share the same cord.

(proof '(has-same-cord deltoid-right biceps-brachii-right ?c ?hx))
:FAIL

ALL-ROOTS (?muscle ?roots)

The *all-roots* rule queries the PLEXBASE facts to find all roots that include motor fibers innervating the muscle. This is done by using a rewrite-rule that references Lisp function *get-all-roots* (that returns a list). Clinical relevance: weakness in the named muscle might reveal damage to the list of roots returned by this query.

(proof '(all-roots biceps-brachii-right ?roots))
?ROOTS = (VENTRAL-HORN-C5-RIGHT VENTRAL-HORN-C6-RIGHT)

ALL-MUSCLES-OF-CORD (?cord ?muscles)

The *all-muscles-of-cord* rule is defined as a rewrite-rule and calls an associated Lisp function get-all-muscles-of-cord that returns a list of muscle names. Prolisp can take a pointer to a list and bind that to a variable. Clinical relevance: Damage to this cord might produce weakness in the list of muscles of the cord.

(proof '(all-muscles-of-cord lateral-cord-right ?muscles))
?MUSCLES = (PRONATOR-QUADRATUS-RIGHT FLEXOR-POLLICIS-LONGUS-RIGHT FLEXOR-DIGITORUM-PROFUNDUS-2-RIGHT FLEXOR-CARPI-RADIALIS-RIGHT BRACHIALIS-RIGHT BICEPS-BRACHII-RIGHT CORACOBRACHIALIS-RIGHT)

ALL-MUSCLES-OF-NERVE (?nerve ?muscles)

The *all-muscles-of-nerve* rule is defined as a rewrite-rule using Lisp function get-all-muscles-of-nerve and binds *?muscles* to a list of muscles that are innervated by axons passing through the named nerve. Clinical relevance: Damage to this nerve might produce weakness in the list of muscles produced by this query.

(proof '(all-muscles-of-nerve median-nerve-right ?muscles))
?MUSCLES = (OPPONENS-POLLICIS-RIGHT SECOND-LUMBRICAL-RIGHT FIRST-LUMBRICAL-RIGHT FLEXOR-POLLICIS-BREVIS-RIGHT ABDUCTOR-POLLICIS-BREVIS-RIGHT PRONATOR-QUADRATUS-RIGHT PALMARIS-LONGUS-RIGHT FLEXOR-POLLICIS-LONGUS-RIGHT FLEXOR-DIGITORUM-SUPERFICIALIS-RIGHT FLEXOR-DIGITORUM-PROFUNDUS-3-RIGHT FLEXOR-DIGITORUM-PROFUNDUS-2-RIGHT FLEXOR-CARPI-RADIALIS-RIGHT)

SHARE-THESE-CORDS (?cord1 ?cord2 ?muscles)

This rule finds muscles that have innervating fibers through the two named cords. Clinical relevance: Weakness in the muscles returned by this query might suggest that both cords have some injury.

(proof '(share-these-cords lateral-cord-right medial-cord-right ?muscles))

?MUSCLES = (FLEXOR-DIGITORUM-PROFUNDUS-2-RIGHT FLEXOR-POLLICIS-LONGUS-RIGHT PRONATOR-QUADRATUS-RIGHT)

SHARE-THESE-ROOTS (?root1 ?root2 ?muscles)

This rule obtains muscles that have efferent fibers from the two different nerve roots. Clinical relevance: Weakness in the listed muscles suggests problems with the named roots. This rule could easily be modified to support three roots.

(proof '(share-these-roots ventral-horn-c7-right ventral-horn-c6-right ?m))
?M = (ANCONIUS-RIGHT CORACOBRACHIALIS-RIGHT TRICEPS-LATERAL-HEAD-RIGHT EXTENSOR-CARPI-RADIALIS-BREVIS-RIGHT FLEXOR-CARPI-RADIALIS-RIGHT TRICEPS-MEDIAL-HEAD-RIGHT TRICEPS-LONG-HEAD-RIGHT EXTENSOR-CARPI-RADIALIS-LONGUS-RIGHT)

Another example finds the muscles that share C7 and C5 roots:

(proof '(share-these-roots ventral-horn-c7-right ventral-horn-c5-right ?m))
?M = (CORACOBRACHIALIS-RIGHT EXTENSOR-CARPI-RADIALIS-BREVIS-RIGHT EXTENSOR-CARPI-RADIALIS-LONGUS-RIGHT)

SENSORY-CONNECTION (?ganglion ?trunk ?division ?cord ?nerve ?dermatome)

The *sensory connection* is a fundamental knowledge element. Using the proof operator, the sensory connection fact base can be queried to bind variables. This example finds trunk/division/cord connection between C7 and C7 dermatome.

(proof '(sensory-connection spinal-ganglion-c7 ?trunk ?division ?cord median nerve dermatome-c7)
?TRUNK = MIDDLE-TRUNK
?DIVISION = ANTERIOR-DIVISION-MIDDLE
?CORD = LATERAL-CORD

GANGLION-SAME-TRUNK (?ganglion1 ?ganglion2 ?trunk ?hx)

This rule finds the trunks containing axons from ganglion1 and ganglion2 and applies intersection giving the common trunk. Clinical relevance: If the trunk is injured then its associated ganglionic axons might demonstrate loss of sensory data. The ?hx variable shows the sensory connections that provided knowledge for the query result.

(proof '(ganglion-same-trunk spinal-ganglion-t1-right ?ganglion2 ?trunk1 ?hx))
?GANGLION2 = SPINAL-GANGLION-C8-RIGHT
?TRUNK1 = INFERIOR-TRUNK-RIGHT
?HX = (HAS-SAME-TRUNK (SENSORY-CONNECTION SPINAL-GANGLION-T1-RIGHT INFERIOR-TRUNK-RIGHT POSTERIOR-DIVISION-INFERIOR-RIGHT MEDIAL-CORD-RIGHT MEDIAL-CUTANEOUS-NERVE-OF-FOREARM-RIGHT DERMATOME-T1-RIGHT) (SENSORY-CONNECTION SPINAL-GANGLION-C8-RIGHT INFERIOR-TRUNK-RIGHT POSTERIOR-DIVISION-INFERIOR-RIGHT MEDIAL-CORD-RIGHT MEDIAL-CUTANEOUS-NERVE-OF-FOREARM-RIGHT DERMATOME-C8-RIGHT))

GANGLION-SAME-DIVISION (?ganglion1 ?ganglion2 ?division ?hx)

This rule finds the common division for the two named spinal ganglia. Clinical relevance: If the division is injured then its associated ganglionic axons might demonstrate loss of sensory data.

(proof '(ganglion-same-division spinal-ganglion-t1-right ?ganglion2 ?div))
?GANGLION2 = SPINAL-GANGLION-C8-RIGHT
?DIV = POSTERIOR-DIVISION-INFERIOR-RIGHT

GANGLION-SAME-CORD (?ganglion1 ?ganglion2 ?cord ?hx)

This rule finds the common cord for the two named spinal ganglia. Clinical relevance: If the cord is injured then its associated ganglionic axons might demonstrate loss of sensory data.

(proof '(ganglion-same-cord spinal-ganglion-t1-right spinal-ganglion-c8-right ?cord ?hx))
?CORD = MEDIAL-CORD-RIGHT
?HX = (HAS-SAME-CORD
(SENSORY-CONNECTION SPINAL-GANGLION-T1-RIGHT INFERIOR-TRUNK-RIGHT POSTERIOR-DIVISION-INFERIOR-RIGHT MEDIAL-CORD-RIGHT MEDIAL-CUTANEOUS-NERVE-OF-FOREARM-RIGHT DERMATOME-T1-RIGHT)
(SENSORY-CONNECTION SPINAL-GANGLION-C8-RIGHT INFERIOR-TRUNK-RIGHT POSTERIOR-DIVISION-INFERIOR-RIGHT MEDIAL-CORD-RIGHT MEDIAL-CUTANEOUS-NERVE-OF-FOREARM-RIGHT DERMATOME-C8-RIGHT))

GANGLION-SAME-NERVE (?ganglion1 ?gangion2 ?nerve ?hx)

The query also returns history data that states trunk information, division information, and cord information. Clinical relevance: If these spinal ganglia are injured, the function of the associated nerve would be lost.

(proof '(ganglion-same-nerve spinal-ganglion-t1-right ?ganglion2 ?nerve))
?GANGLION2 = SPINAL-GANGLION-C8-RIGHT
?NERVE = MEDIAL-CUTANEOUS-NERVE-OF-FOREARM-RIGHT

In this example, the nerve identifier is in the query. The ?hx variable details why the proof succeeded.

(proof '(ganglion-same-nerve spinal-ganglion-c5-right spinal-ganglion-c6-right median-nerve-right ?hx))
?HX = (HAS-SAME-NERVE
(SENSORY-CONNECTION SPINAL-GANGLION-C5-RIGHT SUPERIOR-TRUNK-RIGHT ANTERIOR-DIVISION-SUPERIOR-RIGHT LATERAL-CORD-RIGHT MEDIAN-NERVE-RIGHT DERMATOME-C5-RIGHT)
(SENSORY-CONNECTION SPINAL-GANGLION-C6-RIGHT SUPERIOR-TRUNK-RIGHT ANTERIOR-DIVISION-SUPERIOR-RIGHT LATERAL-CORD-RIGHT MEDIAN-NERVE-RIGHT DERMATOME-C6-RIGHT))

ALL-DERMATOMES-FOR-NERVE (?nerve ?dermatomes)

This rule finds all dermatomes that share axons with this nerve. In the example, the query reveals that the median nerve serves five dermatomes of the hand. Clinical relevance: Injury to this nerve would produce sensory changes in these dermatomes.

(proof '(all-dermatomes-for-nerve median-nerve-right ?dermatomes))
?DERMATOMES = (DERMATOME-T1-RIGHT DERMATOME-C8-RIGHT DERMATOME-C5-RIGHT DERMATOME-C6-RIGHT DERMATOME-C7-RIGHT)

ALL-DERMATOMES-FOR-TRUNK (?trunk ?dermatomes)

This rule finds all dermatomes that have axons that pass through the named trunk.

(proof '(all-dermatomes-for-trunk superior-trunk-right ?dermatomes))
?DERMATOMES = (DERMATOME-C5-RIGHT DERMATOME-C6-RIGHT)

ALL-DERMATOMES-FOR-DIVISION (?division ?dermatomes)

This rule finds all dermatomes with axons passing through the named division.

(proof '(all-dermatomes-for-division anterior-division-superior-right ?answer))
?DERMATOMES = (DERMATOME-C5-RIGHT DERMATOME-C6-RIGHT)

ALL-DERMATOMES-FOR-CORD (?cord ?dermatomes)

This rule finds all dermatomes with axons passing through the named cord.

(proof '(all-dermatomes-for-cord medial-cord-left ?answer))
?ANSWER = (DERMATOME-T1-LEFT DERMATOME-C8-LEFT)

MUSCLE-AND-DERMATOME-SHARE-TRUNK (?muscle ?dermatome ?trunk ?hx)

This rule finds the common trunk for a muscle and a dermatome and returns the query history ?hx.

(proof '(muscle-and-dermatome-share-trunk teres-major-right ?dermatome ?trunk ?hx))
?DERMATOME = DERMATOME-C6-RIGHT
?TRUNK = SUPERIOR-TRUNK-RIGHT
?HX = (MUSCLE-AND-DERMATOME-SHARE-TRUNK SUPERIOR-TRUNK-RIGHT
(MOTOR-CONNECTION VENTRAL-HORN-C5-RIGHT SUPERIOR-TRUNK-RIGHT POSTERIOR-DIVISION-SUPERIOR-RIGHT
POSTERIOR-CORD-RIGHT LOWER-SUBSCAPULAR-NERVE-RIGHT TERES-MAJOR-RIGHT)
(SENSORY-CONNECTION SPINAL-GANGLION-C6-RIGHT SUPERIOR-TRUNK-RIGHT POSTERIOR-DIVISION-SUPERIOR-RIGHT POSTERIOR-CORD-RIGHT AXILLARY-NERVE-RIGHT DERMATOME-C6-RIGHT))

MUSCLE-AND-DERMATOME-SHARE-DIVISION (?muscle ?dermatome ?division)

This rule finds a common division for a muscle and dermatome and returns search history.

(proof '(muscle-and-dermatome-share-division brachioradialis-right dermatome-c5-right ?division ?hx))
?DIVISION = POSTERIOR-DIVISION-SUPERIOR-RIGHT

MUSCLE-AND-DERMATOME-SHARE-CORD (?muscle ?dermatome ?cord)

This rule finds a common cord for a muscle and a dermatome and returns the search history.

(proof '(muscle-and-dermatome-share-cord first-lumbrical-left ?dermatome ?cord ?hx))
?DERMATOME = DERMATOME-C8-LEFT
?CORD = MEDIAL-CORD-LEFT

MUSCLE-AND-DERMATOME-SHARE-NERVE (?muscle ?dermatome ?nerve)

This rule finds a common nerve for a muscle and a dermatome and returns search history.

(proof '(muscle-and-dermatome-share-nerve ?muscle ?dermatome ?nerve ?hx))
?MUSCLE = OPPONENS-DIGIT-MINIMI-LEFT
?DERMATOME = DERMATOME-C8-LEFT
?NERVE = ULNAR-NERVE-LEFT

In this example, the dermatome is named and the query finds a matching muscle with same nerve.

USER(26): (proof '(muscle-and-dermatome-share-nerve ?muscle dermatome-c8-left ?nerve))
?MUSCLE = OPPONENS-DIGITI-MINIMI-LEFT
?NERVE = ULNAR-NERVE-LEFT

In this example, the nerve is stated and the query returns muscle and dermatome that share that nerve.

(proof '(muscle-and-dermatome-share-nerve ?muscle ?dermatome ulnar-nerve-left))
?MUSCLE = OPPONENS-DIGIT-MINIMI-LEFT
?DERMATOME = DERMATOME-C8-LEFT

5. Diagnostic Rules

A set of rules were developed for inclusion in the diagnostic suite of StrokeDx. Benchmark file *superior trunk lesion* was developed to test these diagnostic rules. Future development will include other benchmarks for brachial plexus lesions.

LOSS-OF-SENSATION (?dermatome ?side ?cf ?hx)

This rule queries the patient facts to find if the ?dermatome has loss of sensation. Sub-goals include four of the sensory modalities. The ?hx variable reports on the data that allows the query to succeed. Clinical relevance: Loss of sensation may represent brachial plexus injury, nerve injury, or stroke.

(proof '(loss-of-sensation dermatome-c5 :right ?cf ?hx))
?CF = 1.0
?HX = (LOSS-OF-SENSATION DERMATOME-C5 :RIGHT 1.0 (LOSS-OF-TOUCH DERMATOME-C5 :RIGHT 1.0) (LOSS-OF-VIBRATION DERMATOME-C5 :RIGHT 1.0) (LOSS-OF-PAIN DERMATOME-C5 :RIGHT 1.0) (LOSS-OF-TEMPERATURE DERMATOME-C5 :RIGHT 1.0))

STRENGTH-OF-MUSCLES (?trunk ?side ?cf ?hx)

This rule queries first the PLEXBASE to map from ?trunk to associated muscles. Next, patient data are searched to determine the strength value for each muscle. This data is obtained and used to compute a weakness confidence factor (strength and weakness are inversely related in our CF heuristic). In this example there is good confidence that superior trunk muscles are strong.

USER(21): (proof '(strength-of-muscles superior-trunk :left ?cf ?hx))
CF = 0.9
?HX = (STRENGTH-OF-MUSCLES SUPERIOR-TRUNK :LEFT (STRENGTH CF 0.9) (STRENGTH-DATA ((BICEPS-BRACHII-LEFT 5) (BRACHIALIS-LEFT 5) (BRACHIORADIALIS-LEFT 5) …)))

WEAKNESS-OF-MUSCLES (?trunk ?side ?cf ?hx)

This rule queries PLEXBASE to find muscles of the ?trunk and then the examination data to see if those muscles are weak. The ?hx variable is bound to the individual muscles and their reported strength value (zero is paralyzed). The history variable also returns all muscle names and strength values. Clinical relevance: Specific pattern of muscle weakness may support diagnosis of damage to nerve, plexus, cord, or brain.

(proof '(weakness-of-muscles superior-trunk :right ?cf ?hx))
?CF = 1
?HX = (WEAKNESS-OF-MUSCLES SUPERIOR-TRUNK :RIGHT 0 (WEAKNESS-CF 1) (STRENGTH-OF-MUSCLES SUPERIOR-TRUNK :RIGHT (STRENGTH CF 0) (STRENGTH-DATA ((BICEPS-BRACHII-RIGHT 0) (BRACHIALIS-RIGHT 0) (BRACHIORADIALIS-RIGHT 0) (CORACOBRACHIALIS-RIGHT 0) (DELTOID-RIGHT 0) … (TRICEPS-LONG-HEAD-RIGHT 0) (TRICEPS-MEDIAL-HEAD-RIGHT 0)))))

6. Benchmarks

Standard benchmark files were created to test the decision support system rules for brachial plexus lesions. Benchmark files are discussed below.

The benchmark file for a *superior trunk lesion* was developed and encoded patient information consistent with a superior trunk lesion. The benchmark codes weakness in biceps, deltoids, brachioradialis muscles and encodes C5 dermatome sensory loss and C6 dermatome sensory loss. This benchmark was tested against the superior trunk diagnostic rule and was a near perfect match (as is expected).

The benchmark file for a *middle trunk lesion* is not yet completed but will encode patient information consistent with a middle trunk lesion. The benchmark codes weakness in extensor digitorum, latissimus, and triceps muscles and encodes C7 dermatome sensory loss.

The benchmark file for an *inferior trunk lesion* is not yet completed but will encode patient information consistent with a inferior trunk lesion. The benchmark codes weakness in muscles including flexor digitorum profundus, abductor pollicis brevis, and first dorsal interosseus and encodes C8 dermatome sensory loss and T1 dermatome sensory loss.

7. Brachial Plexus Diagnostic Rules

Prolisp rules (for inclusion in StrokeDx) were created for decision support system for brachial plexus lesions. These rules are discussed below.

Rule Superior Trunk Lesion

The rule for a superior trunk lesion was developed and the rule tests benchmark information for superior trunk lesion. The rule searches for weakness in biceps, deltoids, brachioradialis muscles and C5 dermatome sensory loss and C6 dermatome sensory loss. This rule was tested against the right superior trunk benchmark and was a near perfect match. In competition with other rules in the stroke set, the superior trunk diagnosis yielded the highest CF (1.0). The proof for the left superior trunk yielded CF of 0.37 (essentially "no"). The proof for *right inferior trunk lesion* against right superior trunk benchmark yielded CF of 0.07. The rules can differentiate between the two trunks.

```
(proof '(superior-trunk-lesion :right ?cf ?hx))
?CF = 1.0
?HX = (SUPERIOR-TRUNK-LESION :RIGHT 1.0
(WEAKNESS-OF-MUSCLES SUPERIOR-TRUNK :RIGHT 0
(WEAKNESS-CF 1)
 (STRENGTH-OF-MUSCLES SUPERIOR-TRUNK :RIGHT
(STRENGTH CF 0)
  (STRENGTH-DATA
((BICEPS-BRACHII-RIGHT 0) (BRACHIALIS-RIGHT 0)
(BRACHIORADIALIS-RIGHT 0) (CORACOBRACHIALIS-RIGHT
0) (DELTOID-RIGHT 0) … (TERES-MINOR-RIGHT 0)
(ANCONIUS-RIGHT 0) (FLEXOR-CARPI-RADIALIS-RIGHT 0)
(LATISSIMUS-DORSI-RIGHT 0)  (TRICEPS-LATERAL-HEAD-
RIGHT 0) (TRICEPS-LONG-HEAD-RIGHT 0) (TRICEPS-
MEDIAL-HEAD-RIGHT 0)))))
(LOSS-OF-SENSATION DERMATOME-C5 :RIGHT 1.0 (LOSS-
OF-TOUCH DERMATOME-C5 :RIGHT 1.0)
 (LOSS-OF-VIBRATION DERMATOME-C5 :RIGHT 1.0) (LOSS-
OF-PAIN DERMATOME-C5 :RIGHT 1.0)
 (LOSS-OF-TEMPERATURE DERMATOME-C5 :RIGHT 1.0)))
```

Rule Middle Trunk Lesion

The diagnostic rule for middle trunk lesion was applied to the superior trunk benchmark. Weakness CF of 0.7 and sensory CF of zero average to 0.35 CF. There are some muscles that are shared with the superior trunk and so this CF is not definitely false.

```
(proof '(middle-trunk-lesion :right ?cf ?hx))
?CF = 0.35
?HX = (MIDDLE-TRUNK-LESION :RIGHT 0.35
(WEAKNESS-OF-MUSCLES MIDDLE-TRUNK :RIGHT 0.3
(WEAKNESS-CF 0.7)
(STRENGTH-OF-MUSCLES MIDDLE-TRUNK :RIGHT
(STRENGTH CF 0.3)
 (STRENGTH-DATA ((ANCONIUS-RIGHT 0) (ABDUCTOR-
POLLICIS-LONGUS-RIGHT 5) (CORACOBRACHIALIS-RIGHT
0) (EXTENSOR-CARPI-RADIALIS-BREVIS-RIGHT 0) …
(TRICEPS-LONG-HEAD-RIGHT 0) (TRICEPS-MEDIAL-HEAD-
RIGHT 0)))))
(LOSS-OF-SENSATION DERMATOME-C7 :RIGHT 0.0 (LOSS-
OF-TOUCH DERMATOME-C7 :RIGHT (NORMAL-CF 1.0) 0.0)
(LOSS-OF-VIBRATION DERMATOME-C7 :RIGHT (NORMAL-
CF 1.0) 0.0) (LOSS-OF-PAIN DERMATOME-C7 :RIGHT
(NORMAL-CF 1.0) 0.0) (LOSS-OF-TEMPERATURE
DERMATOME-C7 :RIGHT (NORMAL-CF 1.0) 0.0)))
```

Rule Inferior Trunk Lesion

The rule for inferior trunk lesion was developed and tests patient information for superior trunk lesion. The rule searches for weakness in flexor digitorum, abductor pollicis brevis, and first dorsal interosseus muscles and C8 dermatome sensory loss and T1 dermatome sensory loss. This rule was tested against the superior trunk benchmark and and yielded false CF.

```
(proof '(inferior-trunk-lesion :right ?cf ?hx)) SUPERIOR TRUNK
RIGHT BENCHMARK ?CF = 0.066 ?HX = (INFERIOR-TRUNK-
LESION :RIGHT (CF 0.0665) (WEAKNESS-OF-MUSCLES
INFERIOR-TRUNK :RIGHT 0.8 (WEAKNESS-CF 0.19996)
(STRENGTH-OF-MUSCLES INFERIOR-TRUNK :RIGHT
(STRENGTH CF 0.8)  (STRENGTH-DATA((FLEXOR-
DIGITORUM-PROFUNDUS-3-RIGHT 5) ... (FLEXOR-POLLICIS-
LONGUS-RIGHT 5) (LATISSIMUS-DORSI-RIGHT 0) (FIRST-
LUMBRICAL-RIGHT 5)(SECOND-LUMBRICAL-RIGHT 5)
(THIRD-LUMBRICAL-RIGHT 5) (FOURTH-LUMBRICAL-
RIGHT 5) (OPPONENS-DIGIT-MINIMI-RIGHT
NIL)(OPPONENS-POLLICIS-RIGHT 5) (PECTORALIS-MAJOR-
RIGHT 0) (PECTORALIS-MINOR-RIGHT 0) (PRONATOR-
QUADRATUS-RIGHT 5)(TRICEPS-LATERAL-HEAD-RIGHT 0)
(TRICEPS-LONG-HEAD-RIGHT 0) (TRICEPS-MEDIAL-HEAD-
RIGHT 0)(ABDUCTOR-DIGIT-MINIMI-RIGHT NIL)))))(LOSS-
OF-SENSATION DERMATOME-C8 :RIGHT 0.0 (LOSS-OF-
TOUCH DERMATOME-C8 :RIGHT (NORMAL-CF 1.0) 0.0)
(LOSS-OF-VIBRATION DERMATOME-C8 :RIGHT (NORMAL-
CF 1.0) 0.0) (LOSS-OF-PAIN DERMATOME-C8 :RIGHT
```

```
(NORMAL-CF 1.0) 0.0) (LOSS-OF-TEMPERATURE
DERMATOME-C8 :RIGHT (NORMAL-CF 1.0) 0.0))(LOSS-OF-
SENSATION DERMATOME-T1 :RIGHT 0.0 (LOSS-OF-TOUCH
DERMATOME-T1 :RIGHT (NORMAL-CF 1.0) 0.0) (LOSS-OF-
VIBRATION DERMATOME-T1 :RIGHT (NORMAL-CF 1.0) 0.0)
(LOSS-OF-PAIN DERMATOME-T1 :RIGHT (NORMAL-CF 1.0)
0.0) (LOSS-OF-TEMPERATURE DERMATOME-T1 :RIGHT
(NORMAL-CF 1.0) 0.0)))
```

8. Conclusions

The following conclusions are made from this research effort:

This prototype accurately models the brachial plexus and its connections. The author believes that this is a novel software program. The effort included coding all motor connections and sensory connections in the plexus into an object oriented knowledge base. Total number of object definitions is 248. Each object definition contains 8 anatomic links. Total of number of links in the PLEXBASE is approximately 2784. The PLEXBASE can serve as a knowledge core for future development efforts and research.

PLEXBASE can be accessed by Lisp functions for knowledge lookup. Primitive functions allow PLEXBASE data to be obtained. The fundamental elements, motor connections and sensory connections, encapsulate the necessary parts of this complex natural system. Motor connections describe the efferent peripheral nervous system of the upper extremity and sensory connections described the afferent peripheral nervous system of the upper extremity.

The queries as discussed above support a wide range of knowledge questions regarding the brachial plexus and interactions of the components. The queries are instantaneous and accurate. This software engine might be appropriate for teaching the brachial plexus to medical professions and for clinical diagnostic support.

9. Future Work

Plans include adding new rules to StrokeDx engine for clinical knowledge processing. The rules for lesions of the three trunks, the divisions, the cords, and the peripheral nerves can be developed. Benchmark test files for each disorder can be written to exercise the rules. Differentiation between a central lesion and a peripheral lesion is important in a clinical setting. Decision support for such differentiation can expedite appropriate care and minimize unnecessary costs such a cerebral magnetic resonance imaging or angiographic studies that are typically expensive.

The clinic EMR has a report writer that generates a Lisp file containing code to populate the NEUROBRIDGE patient examination data structure. Research plans include creating EMR test cases for many of the PLEXBASE diagnostic rules. From the test cases, the examination structure can be created. The PLEXBASE software can then be tested on these cases and software validity can be determined. Actual patient data can be downloaded in this manner for testing.

Independent verification and validation (IV&V) are planned for this software system.

Future work includes graphical interface to provide viewing of anatomic structures of the PLEXBASE. Other planned work includes design and development of a Web-based client interface using a server executing the computerized atlas and expert systems. A neurological test, electromyography, yields data regarding peripheral nerves, muscles, nerve roots, and the brachial plexus. EMG data can be added to the PLEXBASE objects, the benchmark files, and the StrokeDx rules.

References

[1] Moore, K.L., & Agur, A.M. (2007). *Essential Clinical Anatomy: Third Edition.* Baltimore: Lippincott Williams & Wilkins. 434-435.

[2] Preston, D, and Shapiro, B, 1998. *Electromyography and neuromuscular disorders*. Butterworth-Heinemann, University of Michigan, pp. 9 - 20.

[3] Gonik B, Zhang N, Grimm MJ. Prediction of brachial plexus stretching during shoulder dystocia using a computer simulation model. Department of Obstetrics and Gynecology, Wayne State University School of Medicine, Sinai-Grace Hospital, Detroit, Michigan 48235, USA

[4] Steele, G, *Common Lisp the Language, 2nd Edition*, Digital Press, 1990.

[5] Keene, S, 1989. *Object-Oriented Programming in Common Lisp: A Programmer's Guide to CLOS*, Addison Wesley, 1989, ISBN: 0201175894.

[6] Sponsler, J, MD, 2012. StrokeDX: A logic programming system to diagnose stroke. *Proceedings of the IASTED Conference for Telehealth*, Innsbruck Austria, February 2012.

[7] Sponsler, J, Frances Van Scoy, Doru Pacurari, 2002. An object oriented neuroanatomic atlas, *Proceedings of the Conference of Artificial Intelligence and Soft Computing*, Banff, Canada, July 2002.

[8] Sponsler, J, 2013. NEUROBRIDGE: An AI development environment for neurology, *Proceedings of the 24th IASTED Conference on Modeling and Simulation*, Banff, Canada, July 17-19, 2013.

[9] Sponsler, J, 2012. StrokeDX: A logic programming system to diagnose stroke. *Proceedings of the IASTED Conference for Telehealth*, Innsbruck Austria, February 2012.

[10] W.F. Clocksin, C.S. Mellish, *Programming in Prolog Third Edition*, Springer-Verlag, New York 1987.

[11] Robinson, JA, A Machine-Oriented Logic Based on the Resolution Principle, *Journal of the ACM* 12:23-44, January 1965.

[12] Stickel, M, R. Waldinger, M. Lowry, T. Pressburger, and I. Underwood. Deductive composition of astronomical software from subroutine libraries. *Proceedings of the Twelfth International Conference on Automated Deduction (CADE-12)*, Nancy, France, June 1994, 341-355.

[13] Carpenter, M, 1978. *Core text of neuroanatomy*. Williams & Wilkins, Baltimore.