A computer program to synthesize American Sign Language

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A program is described that allows experimenters to generate American Sign Language forms by computer. The computer synthesis of such signs could allow major advances in the experimental investigation of the perception of sign language, much as computer-generated speech has done for the study of speech perception.

American Sign Language (ASL) is passed down from one generation of deaf people to the next as an autonomous and native language (Klima & Bellugi, 1979; Lane & Grosjean, 1980). As a visual language, ASL utilizes dimensions of space and movement to transmit information simultaneously about several spatial parameters. These parameters include the configuration of the hands, the location of the hands, and movement of the hands and arms. Strikingly, the key to the grammar of the language lies in large part in processes conveyed by particular patterns of movement and spatial contouring (Klima & Bellugi, 1979), processes having psychological as well as linguistic significance (Poizner, Newkirk, Bellugi, & Klima, 1981). That movement information alone is sufficient to convey these processes has been demonstrated by presenting sign forms as patterns of moving points of light, following Johansson's (1973, 1975) classic procedures for isolating biological motion (Poizner, Bellugi, & Lutes-Driscoll, 1981). Furthermore, the psychological representation of even meaningless ASL movement forms differs between deaf, native signers and hearing observers unfamiliar with ASL (Poizner, 1981).

Investigation of the perception of sign language using only naturally produced stimuli, however, has some severe limitations. Many psycholinguistic experiments require the precise control over stimulus parameters that only computer-generated sign affords; signers, of course, cannot simply be instructed to produce forms exactly equal in trajectory shape, in movement dynamics, or instructed to produce a series of forms that are separated physically by exactly the same increment, and so forth. The present program, listed in Appendix A, allows the user to computer generate sign forms. The

availability of such computer synthesis of sign could well allow major advances in the experimental investigation of the perception of sign language, much as computer-generated speech has done for the study of speech perception.

HARDWARE AND SOFTWARE

The program is written in BASIC and implemented on a Hewlett-Packard 9830A microcomputer with an interfaced data tablet (HP-9864A) and x-y plotter (HP-9862A). The program can thus run on readily available and inexpensive microcomputer systems. It is, however, modifiable for other systems.¹ The program generates a time series of plots of the positions of the joints of the arms and hands for a specified ASL sign. The joints can be connected for a stick-figure representation, or only particular joints themselves can be displayed to synthesize signs as dynamic point-light displays (see Poizner, Bellugi, & Lutes-Driscoll, 1981).

The program consists of two sets of program modules that have been overlaid to circumvent memory limitations of the Hewlett-Packard (7,904 16-bit words of memory). One set of modules (1) sets up an initial skeletal figure (user-specified Operation 1), (2) allows the interactive input, via the data tablet, of functions specifying how joint angles change over time (Operation 3), (3) allows for the storage and retrieval of specified movements (action functions; Operations 5 and 6), and (4) allows for the capability to add two functions together or move a function from one joint angle to another (Operation 7). A second set of program modules takes the skeletal figure description and the digitized action functions and performs the appropriate angular transformations generating a sequence of output plots (Operation 8). The program also provides a spare arm for storage, so that the user can compose a new movement sequence without rebuilding all the time functions.

The heart of the program is the procedure for execut-

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Figure 1. Digits of the hand emerging from the origin after successive transformations are applied (a) to the joint angles of the fingers and (b) to the thumb. PP = proximal phalanx, MP = middle phalanx, DP = distal phalanx, MC = metacarpal, IF = index finger, TH = thumb. See Appendix C for definitions of particular angle function numbers.

ing movements. This procedure involves a sequence of coordinate transformations. Each skeletal point (x , y , z , w) is represented in homogeneous coordinates that provide for simple translations of points using 4 by 4 matrix multiplications (see Newman & Sproull, 1979). Starting with the most distal joints of the arm and hand, a joint is translated to the origin, and a coordinate transformation specified by its angle function (e.g., a particular rotation) is performed on it and on all joints distal to it. That joint and all distal joints are then translated up the y -axis so that the next proximal joint goes to the origin. The appropriate coordinate transformation is then applied, and the procedure iterates until the sternum is at the origin. Appendix B provides parameter definitions and default values for skeletal lengths and initial skeletal angles. The user can obtain a desired initial arm and hand configuration by inserting the appropriate angular values in place of the default values listed in Appendix B.

The user specifies an initial configuration for the joint angles (length and joint angle parameter numbers are given in Appendix B) and defines functions that specify how particular joint angles change over time for

a given ASL sign (angle number definitions are listed in Appendix C). Figure 1 illustrates digits of the hand emerging from the origin after successive transformations are applied to the joint angles of the fingers (Figure 1a) and to the thumb (Figure 1b). Figure 2 shows the arm and hand emerging from the origin after successive transformations are applied to the joint angles of the wrist (Figure 2a), elbow (Figure 2b), and shoulder (Figure 2c). Plots of the position of the figure for any portion of the movement can then be obtained, with the user specifying beginning and ending times and the step size for time increments.

Figure 3 presents sample output from the program. In Figure 3b, four frames of a movement in which the hands pronate (a movement important to ASL) are presented. Figure 3a shows the plot of how the elbow angle that rotates the forearm (Parameter 23, Appendix C) changes over time, reconstructed by the program from digitized input. The resulting change in the position of the arm over time is shown in successive panels of Figure 3b. Frames 1, 7, 13, and 19 of a 20-frame sequence are shown, with animation of these frames producing smooth movement.

Figure 2. Arm and hand emerging from the origin after successive transformations are applied to the (a) joint angles of the wrist, (b) elbow, and (c) shoulder. LF = little finger, RF = ring finger, MF = middle finger, IF = index finger. See Appendix C for definitions of particular angle function numbers.

Figure 3. (a) Change in elbow angle over time of joint that rotates the forearm. (b) Four frames of the resulting movement sequence in which the hands pronate.

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NOTE

1. The program is currently being transferred and extended to run on an Evans and Sutherland Picture System II driven by a PDP-11/34. Information concerning the program is available from Michael Shantz, De Anza Systems, Inc., 118 Sharcot Ave., San Jose, California 95131, and Howard Poizner, Salk Institute for Biological Studies, P.O. Box 85800, San Diego, California 92138.

Appendix A

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10 REM ***** ASLSIM *****
15 REM OPERATION 1 = INITF-INITIALIZE FIGURE
20 REM OPERATION 2 = PLTFIG- PLOT THE FIGURE
25 REM OPERATION 3 = DEFACT- DEFINE ACTION 1-3
30 REM OPERATION 4 = PLTACT- PLOT ACTION FUNCTION
35 REM OPERATION 5 = SAVACT- SAVE ACTION ON TAPE
40 REM OPERATION 6 = UNSACT- FETCH ACTION FROM TAPE
45 REM OPERATION 7 = ADDACT- ADD OR MOVE FUNCTIONS
50 REM OPERATION 8 = DOACT- EXECUTE ACTION ON FIGURE
55 REM -----
410 REM **FIGURE DATA STRUCTURE
420 REM POINTS AND POSITIONS
500 DIM AS[150],BS[70,4]
560 REM ****ACTION DATA STRUCTURES: 27 DEGREES
570 REM OF FREEDOM FOR EACH ARM, 20 TIME INCREMENTS
580 REM IN AN ACTION
600 DIM IS[81,20]
660 REM *** MATRICES AND POINTS
664 DIM LS[4,4],MS[4,4],NS[4,4]
668 DIM OS[4,4]
670 DIM PS[1,4],QS[1,4]
680 DIM RS[1,4],SS[1,4]
980 REM GET FUNCTION TO PERFORM 1 INITF, 2PLTFIG
982 REM 3 DEFACT,4 PLTACT, 5 SAVACT,6 UNSACT, 7 ADDACT,
984 REM 8 DOACT, 9
985 DISP "INITIALIZE FUNCS? 1:";
986 INPUT J
987 IF J<1 OR J>1 THEN 1000
990 FOR I=1 TO 81
991 FOR J=1 TO 20
992 I[I,J]=0
993 NEXT J
994 NEXT I
1000 DISP "ASLSIM OPERATION:";
1020 INPUT A
1040 IF A>0 AND A<9 THEN 1100
1080 DISP "BAD FUNCTION"
1090 GOTO 1000
1100 GOSUB A OF 2000,3000,4000,5000,6000,7000,8000,9000
1200 GOTO 1000
1980 REM ***** INITIALIZE FIGURE *****
2000 DISP "DEFAULT OR MODIFY 0/1:";
2012 INPUT I
2014 IF I=0 THEN 2050
2016 DISP "ENTER PARAMETER#,VALUE:";
2018 INPUT J,K
2020 A[J]=K
2030 DISP "ENTER 1 TO QUIT:";
2032 INPUT K
2034 IF K=1 THEN 2190
2036 GOTO 2016
2050 FOR I=1 TO 150
2052 A[I]=0
2054 NEXT I
2056 FOR I=1 TO 70
2058 FOR J=1 TO 4
2060 B[I,J]=0
2062 NEXT J
2064 NEXT I
2080 REM SET UP ANGLES OF PHALANGES
2090 A[42]=PI/8
2092 A[44]=A[47]=PI/4
2094 A[48]=3*PI/8
2100 FOR I=1 TO 4
2110 J=(I-1)*10+2
2112 A[J]=PI/8
2114 A[J+2]=A[J+5]=PI/4
2116 A[J+6]=0
2118 NEXT I
2120 A[1]=A[3]=A[16]=A[26]=A[31]=A[6]=2
2130 REM SET UP LENGTHS OF HAND BONES
2132 A[5]=4
2134 A[11]=A[21]=2.5
2136 A[13]=3.2
2138 A[15]=A[25]=A[35]=5
2140 A[23]=A[43]=3.5
2142 A[33]=A[41]=3
2144 A[36]=8
2146 A[45]=6
2148 REM SET UP WRIST PARAMS
2150 A[51]=5
2152 A[52]=A[53]=0
2154 REM SET UP ELBOW PARAMS
2156 A[61]=27
2158 A[62]=PI/8
2160 A[64]=3*PI/4
2162 REM SET UP SHOULDER PARAMS
2164 A[67]=30
2166 A[68]=PI/4
2168 A[69]=A[70]=0
2180 FOR I=1 TO 70
2184 A[I+75]=A[I]
2186 NEXT I
2190 RETURN
2995 REM **** PLOT FIGURE ****
3000 DISP "USE DOACT WITH 1,2,1";
3100 WAIT 300
3110 RETURN
3995 REM ****DEFINE ACTION USING DIGITIZER****
3996 REM
4000 DISP "WHICH ACTION, FUNC:";
4020 INPUT X,Y
4040 IF X>0 AND X<4 AND Y>0 AND Y<28 THEN 4100
4060 DISP "BAD ACTION OR FUNCTION NO"
4070 WAIT 100
4080 GOTO 4000
4100 WRITE (9,*)
4110 W=(X-1)*27+Y
4200 FOR T=1 TO 20
4210 ENTER (9,*)P,Q
4220 I[W,T]=Q*0.3927
4260 IF P<T/2.5 THEN 4210
4265 WRITE (9,*)
4270 NEXT T
4300 WRITE (9,*)
4900 RETURN
4995 REM ****PLOT ACTION*****
5000 DISP "WHICH ACTION, FUNCTION:";
5020 INPUT X,Y
5030 SCALE -5,25,-PI,PI
5040 XAXIS 0,2,0,20
5050 YAXIS 0,PI/8,-PI/2,PI/2
5055 PLOT 0,0,1
5056 W=(X-1)*27+Y
5060 FOR T=1 TO 20
5100 PLOT T,I[W,T],2
5200 NEXT T
5220 PEN
5240 WRITE (9,*)
5900 RETURN
5990 REM ****SAVE ACTION ON TAPE****
6000 DISP "FILE:";
6010 INPUT J
6035 FIND J
6075 STORE DATA J,I
6080 RETURN
6990 REM ****FETCH ACTION FROM TAPE****
7000 DISP "FILE:";
7010 INPUT J
7060 FIND J
7070 LOAD DATA J,I
7120 RETURN
7990 REM **** ADD OR MOVE FUNCTIONS****
8000 DISP "ADD OR MOVE 0/1:";
8010 INPUT C
8014 REM 1 MOVE
8016 DISP "FROM ACT,FUNC,TOACT,FUNC:";
8018 INPUT W,X,Y,Z
8020 IF W>0 AND W<4 AND Y>0 AND Y<4 THEN 8030
8022 DISP "ACT 1/2/3=(RIGHT/LEFT/SPARE)";
8023 WAIT 200
8024 GOTO 8016
8030 IF X>0 AND X<28 AND Z>0 AND Z<28 THEN 8040
8032 DISP "VALID FUNCTIONS 1-27";
8033 WAIT 200
8034 GOTO 8016
8040 I=(W-1)*27+X
8042 J=(Y-1)*27+Z
8043 IF C=0 THEN 8060
8044 FOR K=1 TO 20
8046 I[J,K]=I[I,K]
8048 NEXT K
8050 RETURN
8060 REM 2 ADD
8062 FOR K=1 TO 20
8064 I[J,K]=I[J,K]+I[I,K]
8066 NEXT K
8070 RETURN
8990 REM ****EXECUTE AN ACTION ON THE FIGURE
9000 LINK 2
9100 END

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10 REM *****ASLSIM; ASLACT *****
20 REM THIS OPERATION EXECUTES AN ACTION ON THE FIGURE
410 REM **FIGURE DATA STRUCTURE
420 REM POINTS AND POSITIONS
500 REM AS(150),BS(70,4)
560 REM *****ACTION DATA STRUCTURES: 27 DEGREES
570 REM OF FREEDOM FOR EACH ARM, 20 TIME INCREMENTS
580 REM IN AN ACTION
600 REM IS(81,20)
660 REM ***MATRICES AND POINTS
664 REM LS(4,4),MS(4,4),NS(4,4)
668 REM OS(4,4)
670 REM PS(1,4),QS(1,4)
680 REM RS(1,4),SS(1,4)
1000 GOTO 8990
2300 REM SUBROUTINE TO TRANSFORM POINTS
2310 FOR Z=G TO H
2312 FOR W=1 TO 4
2314 P[L,W]=B[Z,W]
2316 NEXT W
2318 MAT Q=P*M
2320 FOR W=1 TO 4
2322 B[Z,W]=Q[L,W]
2324 NEXT W
2350 NEXT Z
2352 RETURN
2995 REM **** PLOT FIGURE****
3000 SCALE -100,+100,-50,+50
3100 OFFSET 0,0
3102 REM 1 PLOT THE SHOULDER,ELBOW,WRIST
3110 W=0
3112 PLOT 0,20,1
3114 S=W+34
3116 PLOT B[S,1],B[S,2],2
3118 S=W+31
3120 PLOT B[S,1],B[S,2],2
3122 S=W+27
3124 PLOT B[S,1],B[S,2],2
3126 S=W+26
3128 PLOT B[S,1],B[S,2],2
3130 S=W+31
3132 PLOT B[S,1],B[S,2],2
3134 S=W+27
3136 PLOT B[S,1],B[S,2],1
3138 S=W+4
3140 PLOT B[S,1],B[S,2],2
3150 REM 2 PLOT THE FINGERS
3152 FOR Z=1 TO 16 STEP 5
3154 S=W+Z
3156 PLOT B[S,1],B[S,2],1
3158 FOR R=1 TO 3
3160 S=S+1
3162 PLOT B[S,1],B[S,2],2
3164 NEXT R
3166 NEXT Z
3180 REM 3 PLOT THE PALM AND THE THUMB
3182 S=W+4
3184 PLOT B[S,1],B[S,2],1
3186 S=W+19
3188 PLOT B[S,1],B[S,2],2
3190 S=W+23
3192 PLOT B[S,1],B[S,2],2
3194 S=W+26
3196 PLOT B[S,1],B[S,2],2
3198 S=W+21
3200 PLOT B[S,1],B[S,2],1
3202 S=W+22
3204 PLOT B[S,1],B[S,2],2
3206 S=W+23
3208 PLOT B[S,1],B[S,2],2
3210 IF W>0 THEN 3230
3220 W=35
3222 GOTO 3112
3230 PFN
3240 RETURN
8990 REM ****EXECUTE AN ACTION ON THE FIGURE
9000 DISP "TIME T1,T2,TSTEP:";
9010 INPUT T,U,V
9020 IF T>0 AND T<U AND U<21 THEN 9050
9030 DISP "BAD TIME SEGMENT."
9040 WAIT 200
9045 GOTO 9000
9049 REM FOR ALL TIME STEPS,L=IDENTITY MATRIX,...
9050 FOR I=T TO U STEP V
9052 FOR J=1 TO 70
9054 B[J,1]=B[J,2]=B[J,3]=0
9056 B[J,4]=1
9058 NEXT J
9060 FOR J=1 TO 4
9070 FOR K=1 TO 4
9080 L[J,K]=1
9090 IF J=K THEN 9100
9094 L[J,K]=0
9100 NEXT K
9110 NEXT J
9119 REM SET TO DO RIGHT ARM, LITTLE FINGER
9120 E=F=0
9122 C=0
9124 X=-1
9126 S=0
9129 REM 1 TRANSLATE DISTAL PHALANX UP Y AXIS
9130 J=E+1
9132 K=F+1
9133 D=C+1
9134 B[J,1]=B[J,3]=0
9136 B[J,2]=A[K]
9138 B[J,4]=1
9140 REM 2 ROTATE DISTAL PHALANX ALPHA ABOUT X AXIS
9142 K=K+1
9144 MAT M=L
9146 M[2,2]=M[3,3]=COS(A[K]+I[D,I])
9148 M[2,3]=SIN(A[K]+I[D,I])
9150 M[3,2]=-M[2,3]
9152 G=H+J
9156 GOSUB 2300
9160 REM 3 TRANSLATE MIDDLE PHALANX UP Y AXIS AND
9162 REM ROTATE BETA ABOUT X AXIS
9164 K=K+1
9166 MAT N=L
9168 N[4,2]=A[K]
9170 MAT O=1
9172 K=K+1
9173 D=D+1
9174 O[2,2]=O[3,3]=COS(A[K]+I[D,I])
9176 O[2,3]=SIN(A[K]+I[D,I])
9178 O[3,2]=-O[2,3]
9180 MAT M=N*O
9182 H=H+1

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9184 GOSUB 2300
9190 REM 4 TRANSLATE PROXIMAL PHALANX C UP Y AXIS,
9192 REM ROTATE GAMMA ABOUT X AND DELTA ABOUT Z
9194 K=K+1
9196 MAT M=L
9198 M[4,2]=A[K]
9200 K=K+2
9201 D=D+1
9202 MAT N=L
9204 N[2,2]=N[3,3]=COS(A[K]+I[D,I])
9206 N[2,3]=SIN(A[K]+I[D,I])
9208 N[3,2]=-N[2,3]
9210 MAT O=M*N
9212 K=K+1
9213 D=D+1
9214 MAT N=L
9216 N[1,1]=N[2,2]=COS(A[K]+I[D,I])
9218 N[1,2]=SIN(A[K]+I[D,I])
9220 N[2,1]=-N[1,2]
9222 MAT M=O*N
9224 H=H+1
9226 GOSUB 2300
9240 REM 5 REPEAT THE ABOVE FOR ALL FINGERS
9250 IF (J-E)>12 THEN 9300
9252 J=J+5
9254 K=K+3
9256 D=D+1
9258 GOTO 9134
9300 REM 6 TRANSLATE THUMB DISTAL PHALANX UP Y AXIS,
9302 REM ROTATE ALPHA ABOUT X AXIS.
9304 J=E+21
9306 K=F+41
9307 D=C+17
9308 MAT N=L
9310 N[4,2]=A[K]
9312 K=K+1
9314 MAT O=L
9316 O[2,2]=O[3,3]=COS(A[K]+I[D,I])
9318 O[2,3]=SIN(A[K]+I[D,I])
9320 O[3,2]=-O[2,3]
9322 MAT M=N*O
9324 G=H+J
9326 GOSUB 2300
9340 REM 7 TRANSLATE THUMB PROXIMAL PHALANX B UP Y AXIS,
9342 REM ROTATE BETA ABOUT X AXIS.
9344 K=K+1
9345 D=C+18
9346 MAT N=L
9348 N[4,2]=A[K]
9350 K=K+1
9352 MAT O=L
9354 O[2,2]=O[3,3]=COS(A[K]+I[D,I])
9356 O[2,3]=SIN(A[K]+I[D,I])
9358 O[3,2]=-O[2,3]
9360 MAT M=N*O
9362 H=H+1
9364 GOSUB 2300
9380 REM 8 TRANSLATE THUMB METACARPAL UP Y,
9382 REM ROTATE GAMMA ABOUT Z,
9386 REM ROTATE DELTA ABOUT Y
9388 K=K+1
9390 MAT M=L
9392 M[4,2]=A[K]
9394 K=K+2
9395 D=C+19
9396 MAT N=L
9398 N[1,1]=N[2,2]=COS(A[K]+I[D,I])
9400 N[1,2]=X*SIN(A[K]+I[D,I])
9402 N[2,1]=-N[2,1]
9404 MAT O=M*N
9406 K=K+1
9407 D=C+20
9408 MAT N=L
9410 N[1,1]=N[3,3]=COS(A[K]+I[D,I])
9412 N[3,1]=X*SIN(A[K]+I[D,I])
9414 N[1,3]=-N[1,3]
9416 MAT M=O*N
9418 H=H+1
9420 GOSUB 2300
9440 REM 9 SPREAD THE METACARPALS ALONG X AXIS
9444 K=F+6
9446 MAT M=L
9454 M[4,1]=X*A[K]
9456 G=E+1
9458 H=E+5
9460 GOSUB 2300
9462 K=F+16
9464 M[4,1]=M[4,1]+X*A[K]
9466 H=E+10
9468 GOSUB 2300
9470 K=F+26
9472 M[4,1]=M[4,1]+X*A[K]
9474 H=E+15
9476 GOSUB 2300
9500 REM 10 TRANSLATE THE FINGERS UP THE Y AXIS
9502 K=F+36
9504 MAT M=L
9506 M[4,2]=A[K]
9508 H=E+20
9510 GOSUB 2300
9520 REM 11 ROTATE WRIST ALPHA ABOUT X, BETA ABOUT Z,
9522 REM
9524 K=F+52
9526 D=C+21
9528 MAT N=L
9530 N[2,2]=N[3,3]=COS(A[K]+I[D,I])
9532 N[2,3]=SIN(A[K]+I[D,I])
9534 N[3,2]=-N[2,3]
9536 K=F+53
9538 D=C+22
9540 MAT O=L
9542 O[1,1]=O[2,2]=COS(A[K]+I[D,I])
9544 O[1,2]=SIN(A[K]+I[D,I])
9546 O[2,1]=-O[1,2]
9548 MAT M=N*O
9550 H=E+25
9552 GOSUB 2300
9560 REM 12 TRANSLATE ULNA TO ORIGIN
9562 K=F+51
9564 MAT M=L
9566 M[4,1]=-X*A[K]
9568 H=E+26
9570 GOSUB 2300
9580 REM 13 TRANSLATE WRIST UP Y AXIS, ROTATE
9582 REM WRIST ALPHA ABOUT Y AXIS, ROTATE
9584 REM FOREARM BETA ABOUT X AXIS.
9585 REM ROTATE HUMERUS ALPHA ABOUT Y AXIS
9586 K=F+61

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9588 D=C+23
9590 MAT N=L
9594 N[4,2]=A[K]
9596 K=F+62
9598 MAT O=L
9600 O[1,1]=O[3,3]=COS(A[K]+I[D,I])
9602 O[1,3]=X*SIN(A[K]+I[D,I])
9604 O[3,1]=-O[1,3]
9606 MAT M=N*O
9608 K=F+64
9610 D=C+24
9612 MAT N=L
9614 N[2,2]=N[3,3]=COS(A[K]+I[D,I])
9616 N[2,3]=SIN(A[K]+I[D,I])
9618 N[3,2]=-N[2,3]
9620 MAT O=M*N
9622 K=F+68
9624 D=C+25
9626 MAT N=L
9628 N[1,1]=N[3,3]=COS(A[K]+I[D,I])
9630 N[1,3]=X*SIN(A[K]+I[D,I])
9632 N[3,1]=-N[1,3]
9634 MAT M=O*N
9636 H=E+27
9638 GOSUB 2300
9650 REM 14 TRANSLATE SHOULDER DOWN Y AXIS TO ORIGIN,
9652 REM ROTATE ARM BETA ABOUT Z, GAMMA ABOUT
9654 REM X, TRANSLATE SHOULDER TO FINAL POSIITON
9656 K=F+67
9658 H=E+34
9660 MAT N=L
9661 B[H,2]=A[K]

9662 N[4,2]=-A[K]
9664 K=F+69
9666 D=C+26
9668 MAT O=L
9670 O[1,1]=O[2,2]=COS(A[K]+I[D,I])
9672 O[1,2]=X*SIN(A[K]+I[D,I])
9674 O[2,1]=-O[1,2]
9676 MAT M=N*O
9678 K=F+70
9680 D=C+27
9682 MAT N=L
9684 N[2,2]=N[3,3]=COS(A[K]+I[D,I])
9686 N[2,3]=X*SIN(A[K]+I[D,I])
9688 N[3,2]=-N[2,3]
9690 MAT O=M*N
9692 MAT N=L
9694 N[4,1]=X*20
9696 N[4,2]=20
9698 MAT M=O*N
9700 GOSUB 2300
9701 REM DO LEFT ARM IF NOT YET DONE
9702 IF E>0 THEN 9730
9704 E=35
9706 F=75
9708 C=27
9709 X=1
9710 GOTO 9130
9720 REM 15 PLOT FIGURE
9730 GOSUB 3000
9732 NEXT I
9900 LINK 1
9990 END

```

Appendix B

Parameter Definitions and Default Values for Skeletal Lengths and Angles for Setting Initial Configurations

Parameter Description	Parameter Number		Default Value*
	Right Arm	Left Arm	
Little Finger (lf)			
length distal phalanx (dp)	1	76	2
angle lfdp alpha (flexion and extension)	2	77	pi/8
length middle phalanx (mp)	3	78	2
angle lfmp beta (flexion and extension)	4	79	pi/4
length proximal phalanx (pp)	5	80	4
length metacarpal (mc)	6	81	2
angle lfpp gamma (flexion and extension)	7	82	pi/4
angle lfpp delta (abduction and adduction)	8	83	0
Ring Finger (rf)			
length rfdp a	11	86	2.5
angle rfdp alpha (flexion and extension)	12	87	pi/8
length rfmp b	13	88	3.2
angle rfmp beta (flexion and extension)	14	89	pi/4
length rfpp c	15	90	5
length rfmc d	16	91	2
angle rfpp gamma (flexion and extension)	17	92	pi/4
angle rfpp delta (abduction and adduction)	18	93	0
Middle Finger (mf)			
length mfdp a	21	96	2.5
angle mfdp alpha (flexion and extension)	22	97	pi/8
length mfmp b	23	98	3.5
angle mfmp beta (flexion and extension)	24	99	pi/4
length mfpp c	25	100	5
length mfmc d	26	101	2
angle mfpp gamma (flexion and extension)	27	102	pi/4
angle mfpp delta (abduction and adduction)	28	103	0

Parameter Description	Parameter Number		Default Value*
	Right Arm	Left Arm	
Index Finger (if)			
length ifdp a	31	106	2
angle ifdp alpha (flexion and extension)	32	107	pi/8
length ifmp b	33	108	3
angle ifmp beta (flexion and extension)	34	109	pi/4
length ifpp c	35	110	5
length ifmc d	36	111	8
angle ifpp gamma (flexion and extension)	37	112	pi/4
angle ifpp delta (abduction and adduction)	38	113	0
Thumb (th)			
length thdp a	41	116	3
angle thdp alpha (flexion and extension)	42	117	pi/8
length thpp b	43	118	3.5
angle thpp beta (flexion and extension)	44	119	pi/4
length thmc c	45	120	6
angle thmc gamma (flexion and extension)	47	122	pi/4
angle thmc delta (abduction and adduction)	48	123	3pi/8
Wrist			
width a	51	126	5
angle (palmar) alpha (flexion and extension)	52	127	0
angle (sideways) beta (radial and ulnar deviation)	53	128	0
Elbow			
length ulna a	61	136	27
pronation and supination angle (rotate forearm) alpha	62	137	pi/8
flexion and extension angle beta	64	139	3pi/4
Shoulder			
length humerus a	67	142	30
rotation angle (about humerus) alpha	68	143	pi/4
angle (outward) beta (abduction and adduction)	69	144	0
angle (forward) gamma (flexion and extension)	70	145	0

*Lengths in centimeters; angles in radians.

Appendix C Angle Function Definitions for Creating Movements

AFN	Anatomical Reference	AFN	Anatomical Reference
Little Finger		Thumb (see Figure 1b)	
1	distal phalanx—alpha (flexion and extension)	17	distal phalanx—alpha (flexion and extension)
2	middle phalanx—beta (flexion and extension)	18	proximal phalanx—beta (flexion and extension)
3	proximal phalanx—gamma (flexion and extension)	19	metacarpal—gamma (flexion and extension)
4	proximal phalanx—delta (abduction and adduction)	20	metacarpal—delta (abduction and adduction)
Ring Finger		Wrist (see Figure 2a)	
5	distal phalanx—alpha (flexion and extension)	21	flexion and extension—alpha
6	middle phalanx—beta (flexion and extension)	22	radial and ulnar deviation—beta
7	proximal phalanx—gamma (flexion and extension)	Elbow (see Figure 2b)	
8	proximal phalanx—delta (abduction and adduction)	23	pronation and supination (wrist rotate)—alpha
Middle Finger		24	flexion and extension—beta
9	distal phalanx—alpha (flexion and extension)	Shoulder (see Figure 2c)	
10	middle phalanx—beta (flexion and extension)	25	rotate about humerus—alpha
11	proximal phalanx—gamma (flexion and extension)	26	abduction and adduction (outward)—beta
12	proximal phalanx—delta (abduction and adduction)	27	flexion and extension (forward)—gamma
Index Finger (see Figure 1a)		Action Number	
13	distal phalanx—alpha (flexion and extension)		Arm
14	middle phalanx—beta (flexion and extension)	1	right
15	proximal phalanx—gamma (flexion and extension)	2	left
16	proximal phalanx—delta (abduction and adduction)	3	spare

Note—AFN = angle function number.