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CHAPTER 15

Some Graphical Procedures for the Preliminary Processing of Longitudinal Data

H. Goldstein, *University of London, U.K.*

Longitudinal or repeated-measurement studies of the physical growth of children are typically designed so that each child is measured at a limited number of 'target' ages or occasions—often every year on his or her birthday. For a sample of children this procedure is designed to yield a set of measurements at each of these occasions. For each measurement, a common approach to summarizing the values thus obtained is to fit a low-order polynomial, typically referred to as a growth curve. An extensive literature on such growth-curve fitting procedures now exists (see Goldstein, 1979), but it usually assumes that each sample member has a measurement at exactly each target occasion. In practice, data are often missing for some occasions (a problem which is relatively straightforward to deal with), and more seriously, many children attend for measurement at times which are close to, but differ somewhat from, the target age.

This chapter will describe one method of 'adjusting' such measurements so that the adjusted values can be treated as if they originated from the target ages. The adequacy of the method will be studied using graphical techniques which will illustrate how those measurements which are inadequately adjusted can be detected, and also how certain kinds of outliers can be detected.

15.1 THE ADJUSTMENT PROCEDURE

Figure 15.1 shows data for a hypothetical child measured at three ages (x_1, x_2, x_3) with corresponding growth measurements (y_1, y_2, y_3). The target age for x_2, i.e. x'_2, is also shown, and the open circle represents the adjusted or target age measurement at x'_2. This is found simply by fitting a suitable curve through the observations and interpolating the value y'_2 at x'_2. Second-degree polynomials are convenient to use, being easily calculated and flexible. Other functional forms are possible but seem to possess no distinct advantages and will not be considered further.

Several questions are immediately apparent about the above adjustment

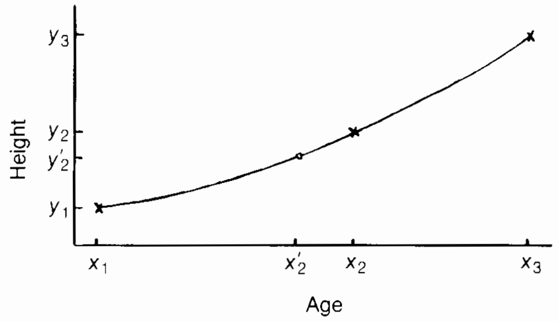

Figure 15.1 An example of adjustment of measured height (y_2) at age x_2 to target age x'_2 and height y'_2. Observed measurements denoted by ×, adjusted measurement by ○

procedure. First, it is clear that when the distance $x_2 - x'_2$ is small, the more 'acceptable' is the adjusted value since any biases are relatively small. Secondly, it is also clear that the adjustment procedure is in general more acceptable the smaller the distance $x_3 - x_1$, since the polynomial adjustment curve should then be a better representation of the true growth curve. Thirdly, if we wish to adjust x_1 to x'_1 where there are no observations at occasions below this, what curve should we use? Finally, are there any advantages to be gained from including further points and higher-degree polynomials? The first two of these points form the basis of the graphical analyses in the remainder of this paper. In response to the last two questions we argue as follows.

Adjacent adjusted measurements will, by definition, lie on polynomials of degree p with p points in common. If p is reasonably large this would effectively induce long-term regularities into the data and allow distant occasions to influence adjusted values. Since it seems desirable for the adjusted values to retain as much as possible of the true measurement variation, p should be as small as possible. A quadratic curve centred on the measurement to be adjusted provides a symmetric procedure, which a linear adjustment would not, and so seems to be the appropriate one to use in general. For an end-point adjustment, however, a straight line seems more appropriate than a quadratic since the latter uses relatively distant information. Consequently, however, the end-point adjustments may not be so satisfactory.

15.2 DATA ANALYSIS

The data to be analysed are measurements of height, weight and triceps skinfold made on a sample of 62 children at five target ages (5.0, 6.0, 7.0, 8.0, 9.0 years) (Tanner *et al.*, 1976). For each measurement of each child, adjusted values were calculated as described in the previous section. There were no missing data, so that for the first or last target ages (denoted by x_5 and x_9) linear adjustment was used, and for x_6, x_7, x_8 quadratic adjustment was used. The data are presented in full in Table 15.1, for the single growth measure, height; age, height, target age and adjusted height are given for each of the 62 children, with five sets of measurements on each.

Figure 15.2 shows a scatterplot at age 6.0 years of the difference between the observed and adjusted values of height against the difference between the actual and target ages. This reflects the expected linear relationship for these relatively small adjustments, with an increasing variance of $y_6' - y_6$ as $x_6 - x_6'$ increases. (The variance is zero at $x_6 = x_6'$.) At first sight one or both of the points ringed seem like outliers, reflecting the inadequacy of too large an adjustment. Because of the increasing variance, however, we need to standardize the variance before being able to study outliers. If this can be done satisfactorily, then it may be possible to use the outliers in order to investigate the first two points about the adequacy of the adjustment procedure.

15.3 STANDARDIZATION FOR VARIANCE

In order to allow for the changing variance we need to specify a functional relationship with $x_i - x_i'$. In the region of the target occasion, we assume that growth is linear. We have

$$y_i = \alpha + \beta x_i + \varepsilon_i.$$

Then

$$\text{var}\,(y_i - y_i' \mid x_i - x_i') = 2\sigma^2(1 - \rho_{ii}),$$

where y_i' is the value of the measurement at the target age x_i', σ^2, the variance of ε_i, is constant, and ρ_{ii} is the correlation between y_i, y_i'. Now $\rho_{ii} = 1$ if $x_i = x_i'$ and decreases as $x_i - x_i'$ increases.

One reasonable choice for relating ρ_{ii} to $x_i - x_i'$ is

$$\rho_{ii} = \exp(-A \mid x_i - x_i' \mid^K)$$

which gives to a first approximation

$$\text{var}(y_i - y_i' \mid x_i - x_i') \propto |x_i - x_i'|^K.$$

We now can study the residuals from the weighted regression of $y_i - y_i'$ on $x_i - x_i'$, standardizing the residuals by their estimated standard errors. These are given by

$$\text{S.E. (residual at } x_i - x_i') = \{\sigma^2[1 - w_i(x_i - x_i')^2/S_x^2]/w_i\}^{1/2},$$

Table 15.1 Ages, heights, target ages and adjusted heights for 62 children (basic data from Tanner *et al.*, 1976)

Serial number	Age	Height value	Target age	Adjusted value	Serial number	Age	Height value	Target age	Adjusted value
1	5.055	110.0	5.0	109.64	2	5.022	113.1	5.0	112.95
1	6.164	117.3	6.0	116.22	2	6.091	120.4	6.0	119.80
1	7.071	123.3	7.0	122.89	2	7.008	126.2	7.0	126.14
1	8.030	127.7	8.0	127.56	2	7.992	133.7	8.0	133.75
1	9.082	132.6	9.0	132.22	2	9.134	140.2	9.0	139.44
3	5.030	113.6	5.0	113.40	4	5.041	109.6	5.0	109.37
3	6.085	120.7	6.0	120.12	4	6.071	115.3	6.0	114.88
3	7.008	127.1	7.0	127.05	4	7.052	121.4	7.0	121.06
3	7.986	133.0	8.0	133.09	4	7.997	127.8	8.0	127.82
3	9.087	140.0	9.0	139.45	4	9.030	134.4	9.0	134.21
5	5.161	104.3	5.0	103.13	6	5.000	108.6	5.0	108.60
5	6.084	111.0	6.0	110.41	6	6.038	116.2	6.0	115.94
5	6.964	116.9	7.0	117.13	6	7.008	122.4	7.0	122.35
5	7.961	122.7	8.0	122.96	6	7.972	127.7	8.0	127.86
5	9.013	130.5	9.0	130.40	6	9.024	133.7	9.0	133.56
7	5.006	101.5	5.0	101.47	8	5.022	95.5	5.0	95.37
7	6.025	107.4	6.0	107.24	8	6.016	101.2	6.0	101.12
7	6.981	114.0	7.0	114.12	8	6.975	105.6	7.0	105.72
7	7.959	119.5	8.0	119.74	8	7.953	110.6	8.0	110.84
7	9.006	125.9	9.0	125.86	8	9.211	117.0	9.0	115.93
9	5.011	102.3	5.0	102.27	10	5.025	112.8	5.0	112.60
9	6.394	106.5	6.0	104.86	10	6.178	121.8	6.0	120.49
9	7.383	112.2	7.0	109.60	10	7.107	128.2	7.0	127.46
9	7.967	117.1	8.0	117.33	10	8.008	134.5	8.0	134.45
9	8.981	122.2	9.0	122.30	10	9.197	142.1	9.0	140.84
11	5.005	104.6	5.0	104.56	12	5.008	112.5	5.0	112.44
11	6.003	112.7	6.0	112.68	12	6.038	119.8	6.0	119.54
11	6.962	118.0	7.0	118.19	12	7.096	126.5	7.0	125.87
11	8.011	122.5	8.0	122.45	12	8.036	132.8	8.0	132.57
11	8.948	126.9	9.0	127.14	12	9.011	138.8	9.0	138.73
13	5.022	106.4	5.0	106.26	14	5.039	98.1	5.0	97.87
13	6.013	112.5	6.0	112.43	14	6.011	103.8	6.0	103.75
13	7.049	116.5	7.0	116.25	14	7.011	106.7	7.0	106.64
13	8.033	122.6	8.0	122.42	14	8.094	114.7	8.0	114.10
13	9.046	127.4	9.0	127.18	14	9.050	119.8	9.0	119.53
15	5.055	115.2	5.0	114.87	16	5.027	114.1	5.0	113.94
15	6.009	121.0	6.0	120.94	16	6.000	120.0	6.0	120.00
15	7.014	128.1	7.0	128.02	16	7.038	126.2	7.0	125.96
15	8.044	133.2	8.0	132.95	16	8.041	132.8	8.0	132.53
15	9.006	139.5	9.0	139.46	16	8.991	138.9	9.0	138.96

Table 15.1 Continued

Serial number	Age	Height value	Target age	Adjusted value	Serial number	Age	Height value	Target age	Adjusted value
17	5.024	110.1	5.0	109.94	18	5.107	114.6	5.0	113.95
17	5.991	116.6	6.0	116.56	18	6.045	120.3	6.0	120.03
17	6.983	121.3	7.0	121.38	18	7.005	125.9	7.0	125.87
17	8.038	126.7	8.0	126.50	18	8.055	131.1	8.0	130.79
17	9.038	132.1	9.0	131.89	18	8.986	137.1	9.0	137.19
19	5.008	109.8	5.0	109.75	20	5.013	109.1	5.0	109.03
19	5.981	115.8	6.0	115.91	20	5.967	114.4	6.0	114.58
19	6.997	121.2	7.0	121.22	20	6.980	119.9	7.0	120.02
19	8.038	128.4	8.0	128.14	20	7.980	126.5	8.0	126.62
19	8.951	134.5	9.0	134.83	20	8.980	131.7	9.0	131.80
21	5.011	106.4	5.0	106.34	22	5.096	103.5	5.0	102.95
21	5.969	111.6	6.0	111.77	22	6.047	108.9	6.0	108.59
21	6.986	117.5	7.0	117.58	22	7.003	116.2	7.0	116.18
21	8.082	123.3	8.0	122.88	22	8.003	122.2	8.0	122.18
21	9.117	128.4	9.0	127.82	22	8.957	127.0	9.0	127.22
23	5.077	110.0	5.0	109.57	24	5.077	108.9	5.0	108.37
23	6.170	116.1	6.0	115.00	24	6.170	116.4	6.0	115.25
23	6.956	121.9	7.0	122.18	24	6.956	121.6	7.0	121.86
23	8.112	127.5	8.0	126.95	24	8.112	127.5	8.0	126.92
23	8.970	131.8	9.0	131.95	24	8.970	132.0	9.0	132.16
25	5.045	117.5	5.0	117.21	26	5.055	110.5	5.0	110.19
25	6.003	123.6	6.0	123.58	26	5.951	115.5	6.0	115.78
25	7.049	131.3	7.0	130.98	26	6.951	121.2	7.0	121.45
25	8.192	137.8	8.0	136.50	26	7.940	125.9	8.0	126.21
25	8.907	143.4	9.0	144.13	26	8.942	131.4	9.0	131.72
27	5.049	111.1	5.0	110.83	28	5.055	110.4	5.0	110.10
27	6.194	117.5	6.0	116.33	28	5.970	115.4	6.0	115.58
27	7.011	122.8	7.0	122.73	28	7.126	122.8	7.0	122.08
27	8.109	128.8	8.0	128.21	28	8.101	127.6	8.0	127.04
27	9.107	134.1	9.0	133.53	28	8.962	132.9	9.0	133.13
29	5.047	105.1	5.0	104.85	30	5.063	103.2	5.0	102.79
29	5.967	109.9	6.0	110.07	30	5.964	109.1	6.0	109.30
29	6.943	114.8	7.0	115.09	30	7.074	114.3	7.0	113.96
29	8.088	120.9	8.0	120.48	30	7.899	118.0	8.0	118.51
29	8.935	124.6	9.0	124.88	30	9.137	125.1	9.0	124.31
31	5.052	105.1	5.0	104.87	32	5.066	107.5	5.0	107.01
31	5.961	109.1	6.0	109.30	32	6.082	115.0	6.0	114.39
31	6.937	115.0	7.0	115.35	32	7.027	122.1	7.0	121.91
31	8.046	120.5	8.0	120.26	32	8.082	129.0	8.0	128.48
31	8.931	125.3	9.0	125.67	32	9.063	135.1	9.0	134.71

Table 15.1 Continued

Serial number	Age	Height value	Target age	Adjusted value	Serial number	Age	Height value	Target age	Adjusted value
33	5.052	109.5	5.0	109.20	34	5.093	112.3	5.0	111.72
33	6.140	115.8	6.0	114.87	34	6.071	118.4	6.0	117.97
33	6.948	121.8	7.0	122.15	34	7.063	124.2	7.0	123.84
33	7.907	127.6	8.0	128.11	34	8.071	129.7	8.0	129.35
33	9.077	133.3	9.0	132.92	34	9.145	134.2	9.0	133.59
35	5.030	109.0	5.0	108.80	36	5.038	108.8	5.0	108.55
35	6.046	115.9	6.0	115.59	36	6.035	115.3	6.0	115.10
35	7.222	123.8	7.0	122.44	36	7.033	120.0	7.0	119.83
35	8.024	128.2	8.0	128.06	36	8.027	125.4	8.0	125.25
35	9.211	135.2	9.0	133.96	36	9.044	131.5	9.0	131.24
37	5.011	113.5	5.0	113.43	38	5.003	115.5	5.0	115.48
37	6.027	120.1	6.0	119.93	38	6.005	122.9	6.0	122.87
37	6.994	125.8	7.0	125.83	38	6.997	129.0	7.0	129.02
37	8.011	131.4	8.0	131.34	38	8.014	136.0	8.0	135.91
37	9.063	136.8	9.0	136.48	38	8.995	142.2	9.0	142.23
39	5.090	106.9	5.0	106.42	40	5.099	105.8	5.0	105.42
39	6.005	111.8	6.0	111.77	40	6.003	109.3	6.0	109.29
39	6.984	116.9	7.0	116.99	40	6.984	114.2	7.0	114.27
39	7.981	123.2	8.0	123.30	40	8.011	117.8	8.0	117.76
39	9.047	127.7	9.0	127.50	40	9.036	122.6	9.0	122.43
41	5.211	101.9	5.0	100.06	42	5.038	109.3	5.0	109.07
41	6.003	108.8	6.0	108.78	42	5.964	114.9	6.0	115.11
41	7.003	116.0	7.0	115.98	42	6.994	120.7	7.0	120.73
41	8.039	122.1	8.0	121.87	42	8.013	125.9	8.0	125.83
41	8.995	127.8	9.0	127.83	42	8.970	130.7	9.0	130.85
43	5.030	101.2	5.0	100.99	44	5.013	113.2	5.0	113.14
43	6.016	108.0	6.0	107.90	44	6.005	118.0	6.0	117.98
43	6.997	113.4	7.0	113.42	44	7.002	123.0	7.0	122.99
43	8.016	118.8	8.0	118.71	44	8.022	127.4	8.0	127.28
43	9.104	125.1	9.0	124.50	44	8.975	133.4	9.0	133.56
45	5.032	105.1	5.0	104.92	46	5.014	112.8	5.0	112.71
45	5.978	110.3	6.0	110.41	46	5.970	118.9	6.0	119.09
45	7.002	114.7	7.0	114.69	46	6.959	125.3	7.0	125.53
45	8.035	121.7	8.0	121.51	46	7.998	130.3	8.0	130.31
45	9.076	125.6	9.0	125.32	46	8.970	135.9	9.0	136.07
47	5.115	107.1	5.0	106.41	48	5.265	102.9	5.0	101.17
47	5.929	112.0	6.0	112.42	48	6.367	110.1	6.0	108.10
47	6.984	118.2	7.0	118.29	48	7.096	112.9	7.0	112.47
47	8.030	123.3	8.0	123.15	48	8.145	118.9	8.0	118.15
47	9.074	128.5	9.0	128.13	48	9.126	123.3	9.0	122.73

Table 15.1 Continued

Serial number	Age	Height value	Target age	Adjusted value	Serial number	Age	Height value	Target age	Adjusted value
49	5.011	112.2	5.0	112.12	50	5.110	110.7	5.0	110.11
49	6.030	120.0	6.0	119.77	50	6.019	115.6	6.0	115.50
49	7.074	127.8	7.0	127.30	50	7.082	121.5	7.0	121.06
49	8.003	133.5	8.0	133.48	50	7.992	126.3	8.0	126.34
49	9.071	140.0	9.0	139.57	50	9.063	132.2	9.0	131.85
51	5.014	110.5	5.0	110.41	52	5.038	110.8	5.0	110.50
51	6.052	117.0	6.0	116.69	52	6.055	118.8	6.0	118.40
51	7.145	123.0	7.0	122.17	52	7.044	125.3	7.0	125.02
51	8.063	128.5	8.0	128.15	52	8.066	131.5	8.0	131.08
51	9.066	133.6	9.0	133.26	52	9.063	138.1	9.0	137.68
53	5.008	111.4	5.0	111.34	54	5.024	99.0	5.0	98.89
53	6.099	120.0	6.0	119.29	54	6.057	103.8	6.0	103.54
53	7.077	126.3	7.0	125.80	54	7.060	108.1	7.0	107.85
53	8.074	132.8	8.0	132.31	54	8.052	112.1	8.0	111.87
53	9.110	139.8	9.0	139.06	54	9.065	117.1	9.0	116.78
55	5.020	99.4	5.0	99.29	56	5.005	112.7	5.0	112.66
55	6.014	104.8	6.0	104.73	56	6.044	120.0	6.0	119.70
55	7.105	109.9	7.0	109.36	56	7.033	126.4	7.0	126.18
55	8.042	115.1	8.0	114.90	56	8.074	133.7	8.0	133.22
55	9.179	119.5	9.0	118.81	56	9.033	139.4	9.0	139.20
57	5.024	110.7	5.0	110.56	58	5.017	106.9	5.0	106.79
57	6.041	116.7	6.0	116.46	58	6.088	113.9	6.0	113.38
57	7.027	122.4	7.0	122.23	58	6.984	118.7	7.0	118.79
57	8.027	128.9	8.0	128.74	58	8.000	124.6	8.0	124.60
57	9.033	133.9	9.0	133.74	58	8.981	129.4	9.0	129.49
59	5.014	116.3	5.0	116.21	60	5.039	106.2	5.0	105.96
59	6.030	122.7	6.0	122.50	60	6.052	112.5	6.0	112.20
59	7.006	129.3	7.0	129.26	60	7.008	117.7	7.0	117.66
59	8.003	135.4	8.0	135.38	60	8.003	123.4	8.0	123.38
59	8.978	141.7	9.0	141.84	60	8.984	128.2	9.0	128.28
61	5.003	104.8	5.0	104.78	62	5.005	114.2	5.0	114.17
61	6.019	111.9	6.0	111.78	62	5.991	120.4	6.0	120.46
61	6.975	117.3	7.0	117.45	62	7.044	127.1	7.0	126.82
61	7.997	123.7	8.0	123.72	62	8.060	133.5	8.0	133.14
61	8.995	128.8	9.0	128.83	62	9.057	139.1	9.0	138.78

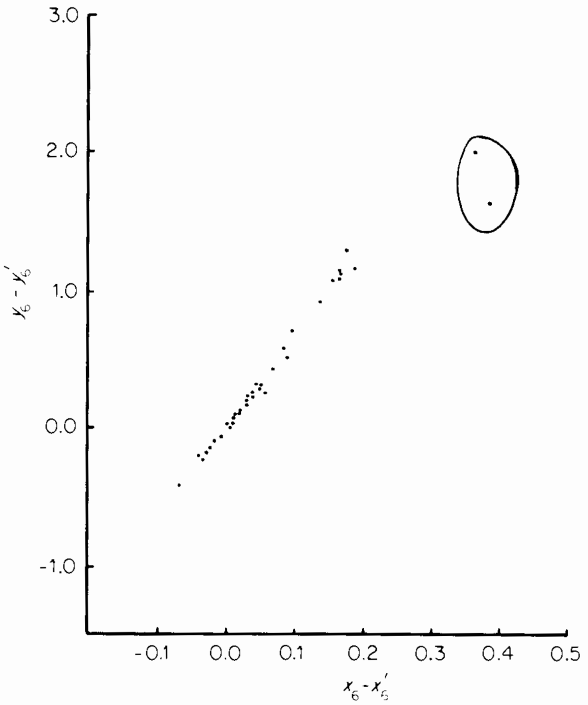

Figure 15.2 Height of 62 children at age 6. Scatter-plot of difference between observed and adjusted measurement $(y_6 - y_6')$ against difference between actual and target age $(x_6 - x_6')$

where

σ^2 = residual mean square,
w_i = regression weight = $|x_i - x_i'|^K$,
$S_x^2 = \Sigma\, w_i(x_i - x_i')^2$.

Note that the regression line is forced to go through the origin.

Figure 15.3 shows the standardized residuals plotted against the fitted values from a linear regression fitted to the data of Figure 15.2 with $K = 1$. It is clear that the variance of these increases with increasing $|x_i - x_i'|$ with a single large negative residual at (2.3, −5.3)

Figure 15.4 is similar to Figure 15.3 but taking $K = 2$ and this seems to make a satisfactory allowance for the variance, no pattern in residuals being apparent and the outlier in Figure 15.3 no longer an extreme value. Similar residual plots have been studied for other ages and variables and the value $K = 2$ seems to be generally satisfactory and is used in the remainder of this chapter. Note that there are no obvious outliers in Figure 15.4.

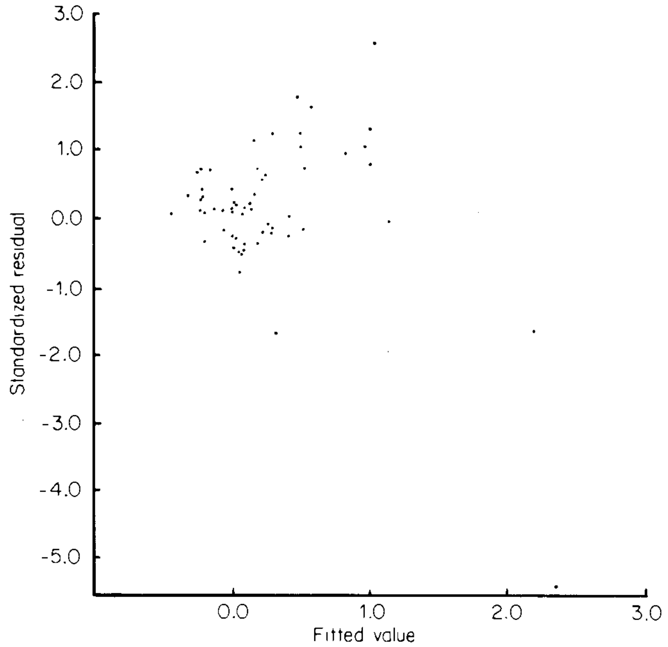

Figure 15.3 Standardized residuals for weighted linear regression with $K = 1$ against fitted values for data in Figure 15.2. Equation of fitted line is $y = 6.037x$

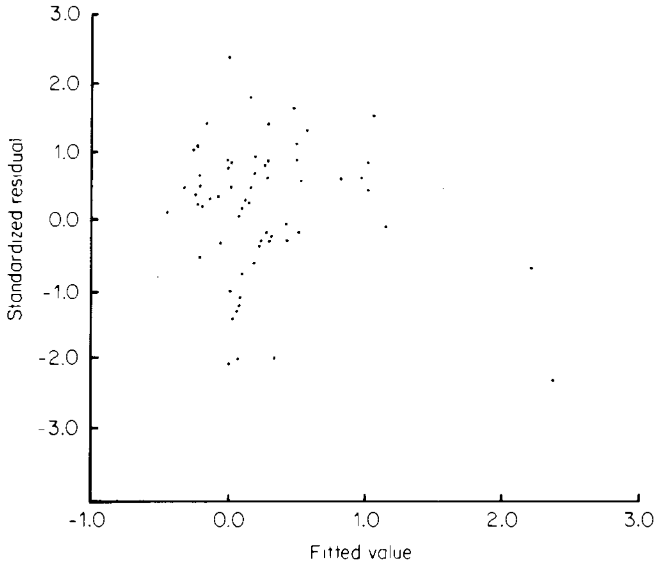

Figure 15.4 Standardized residuals from weighted linear regression with $K = 2$ plotted against fitted values for data in Figure 15.2. Equation of fitted line is $y = 6.074x$

15.4 OUTLIER DETECTION

In the remainder of the chapter we consider some of the outliers in the data and offer an interpretation of their significance. Figure 15.5 shows the residual plot for height measurements at age 9, with the most extreme residual being for child number 25. Figure 15.6 shows the growth measurement for this child from which it is clear that the adjusted measurement is in

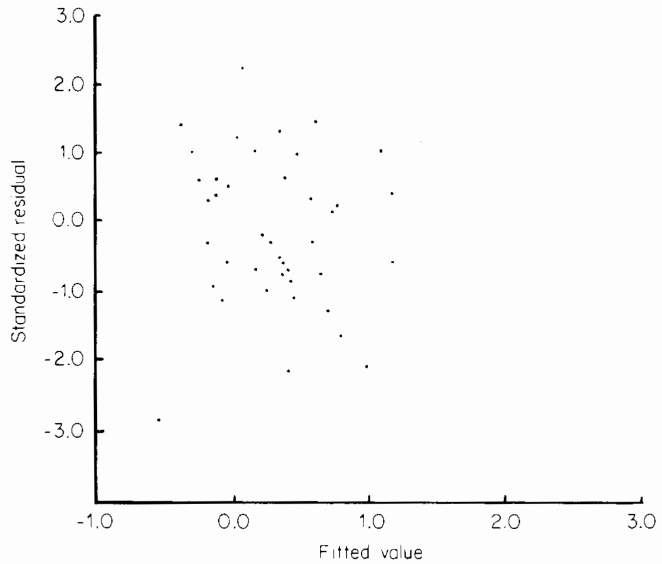

Figure 15.5 Residual plot ($K = 2$) at age 9 for height measurements

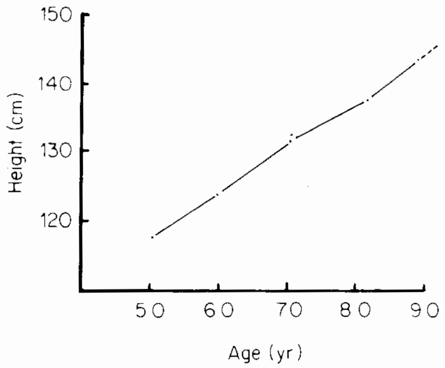

Figure 15.6 Plot of height measurements for child 25

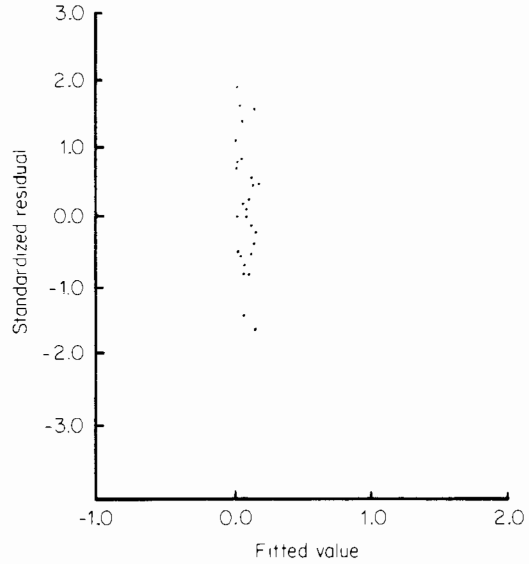

Figure 15.7 Residual plot ($K = 2$) at age 5 for height measurements. Subset of residuals only

fact an extrapolation outside the range of observed values and is also the 'earliest' measurement at this age. Nevertheless, the measurement itself is not very extreme and in practice we probably would not wish to exclude it from the data.

Figure 15.7 shows a plot of a subset of the standardized residuals at age 5 for height, with child number 9 as an outlier. In fact this child's growth rate was only 2.6 cm/yr, between 5 and 6 years, which is below the first percentile of the appropriate velocity standards (Tanner *et al.*, 1966), so that the adjustment for this child becomes too small in comparison to the other children. In this case, therefore, the procedure detects a measurement outlier rather than an inappropriate adjustment.

Figure 15.8, likewise, is detecting an outlier (child 25) resulting from extreme measurements of weight. This child has a growth velocity from 6–7 years below the first percentile and from 7–8 years above the 99th percentile, leading to an adjustment which is too large and suggesting that the 7-year measurement may be too low.

Finally, Figure 15.9 shows a subset of standardized residuals from skinfold measurement at age 7 with child 25 again having a large positive outlier. Figure 15.10 shows the actual skinfold measurements for child 25, illustrating as before that a small growth velocity followed by a large one is not well approximated by a quadratic curve. In this case, since the pattern is the same as with weight, we may be inclined to accept the measurements as accurate,

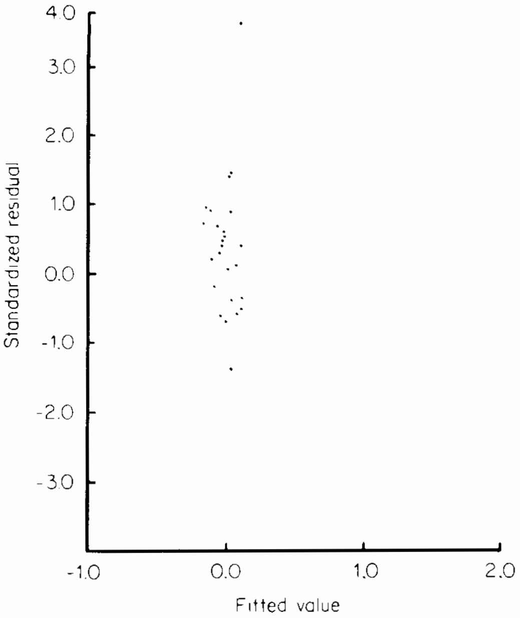

Figure 15.8 Residual plot ($K = 2$) at age 7 for weight measurements. Subset of residuals only

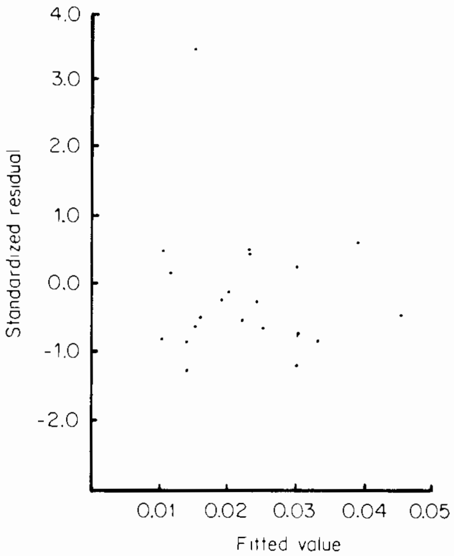

Figure 15.9 Residual plot ($K = 2$) at age 7 for triceps skinfold measurements. Subset of residuals only

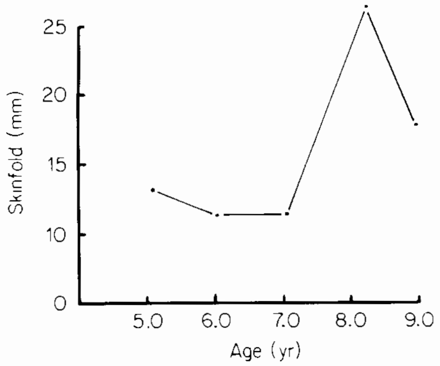

Figure 15.10 Plot of skinfold measurements for child 25

although the possibility of, for example, an incorrectly recorded age would need to be investigated. If the measurements are accepted, then we might prefer to use a linear adjustment using ages 6 and 7 (which here would cover the target age) rather than a quadratic.

15.5 CONCLUSIONS

We have shown how residual plots of adjusted measurements can detect outliers resulting from a number of causes. The examples have been used to illustrate typical findings. As a rule, outliers for large values of $x_i - x_i'$ indicate an inappropriate adjustment, either through too large a distance or with measurements too far apart for the adjusting curve to be used satisfactorily. Those outliers occurring with small values of $x_i - x_i'$ tend to reflect data errors, but may also indicate that a different order polynomial should be used for adjustment.

The procedure described can be fully automated to detect outliers and produce relevant data plots so that editing decisions can be made. It could usefully be adopted routinely for the preliminary processing of longitudinal growth data.

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