The selection of suitable indices for the measurement and analysis of fish condition

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The selection of suitable indices for the measurement and analysis of fish condition

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A survey of the studies published in two leading fisheries journals revealed that the analysis and measurement of condition, based on length–weight data, has been performed using a wide variety of indices and statistical procedures. Eight forms of index were identified which can be categorized into those which measure the condition of individual fish, i.e. 'condition factors', and those which measure the condition of subpopulations as a whole, i.e. regressions of $\log_{10}$ weight on $\log_{10}$ length and the parameters of such regressions. Analysis of a test data set indicated that both the form of index and properties of the data set size can dictate the patterns of condition observed. The various indices were reviewed in terms of appropriateness, simplicity and statistical correctness. It was concluded that an index should be selected only after a detailed examination of both the underlying assumptions of the index and the properties of the data set.

I. INTRODUCTION

The study of condition, now standard practice in fisheries ecology, is usually based on the analysis of length–weight data and assumes that heavier fish of a given length are in better condition. It is believed to be a good indicator of the general 'well-being or fitness' of the population under consideration, while growth, defined as a combination of increases in body length, condition and tissue energy concentration, represents the ultimate expression of this fitness (Adams & McLean, 1985; Booth & Keast, 1986). Condition has been most effectively used in three kinds of population analysis (Weatherley, 1972): (i) in comparing monospecific populations living under apparently similar, or apparently different, conditions of food density, climate etc. (e.g., Stucky & Klaassen, 1971; Wootton *et al.*, 1978; Wierner & Hannenan, 1982); (ii) in determining the timing and duration of gonad maturation (e.g., Htun-Han, 1978; Dadzie & Wangila, 1980; Chang & Navas, 1984); and (iii) as an indication of changing gross nutritional balance during chronic alterations in feeding activity or food supply (e.g., Caulton & Bursell, 1977; De Silva, 1985; White & Fletcher, 1985; Booth & Keast, 1986).

Other indices have also been used to evaluate the well-being or fitness of fish populations. These include a liver index (hepatosomatic index) (Htun-Han, 1978; Jensen, 1979); body water content (Elliott, 1976); visceral-somatic index (Delahunty & DeVlaming, 1980; Adams & McLean, 1985); gut index (Jensen, 1980); protein–energy ratio (P : E) (Bowen, 1979); RNA/DNA ratios of liver and muscle (Bulow *et al.*, 1981); calorific values of fish tissues, including protein and lipid fractions (Booth & Keast, 1986; Hails, 1983); and partial condition factors (Iles, 1984). However, these indices usually require time-consuming laboratory analysis unlike indices of basic condition which only require raw length–weight data. Changes in condition, based on length–weight data, reflect normal seasonal

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fluctuations in metabolic balance, patterns of maturation, and even state and fullness of the alimentary canal (Weatherley, 1972). Such changes do not include information on nutritional status and Booth & Keast (1986) have pointed out that ' total energy growth ' can theoretically occur independently of changes in body weight. In practice, therefore, considerable care is needed when interpreting changes in condition as measured by indices based solely on length–weight data.

While most studies of the life histories of fish describe changes in the condition of the species, few papers have been published which discuss the methods of measuring and analysing such changes. The two most frequently cited papers in the general area of length–weight relationships are those of Le Cren (1951) and Ricker (1973) (190 and 286 citations, respectively, in *Science Citation Index* up to the end of 1986). Both authors recommended specific techniques for analysing length–weight data, yet the measurement and analysis of condition is still performed using a wide variety of indices, relationships and statistical procedures (Table I). This is due not only to the availability of computer software, which makes elaborate analyses easily accessible, but also to the diversity of opinion as to the most suitable index and a failure to examine the underlying assumptions of each index and statistic. Ricker (1973) suggested that " the excuse for the (biologist) entering the field is that outstanding problems in fisheries mainly concern the selection and interpretation of parameters rather than their computation ". Therefore, we have reviewed, in a manner which involved minimal mathematical or statistical analysis, the various indices which have been used in the study of fish condition, and have attempted to highlight the problems associated with their use.

II. PROCEDURE

The measurements of condition employed in papers published in *Journal of Fish Biology* and *Transactions of the American Fisheries Society* (1969–1986) have been categorized, and their frequency of occurrence is illustrated in Fig. 1. These and other related forms were then reviewed using three criteria: appropriateness, simplicity, and statistical correctness. Hurlbert (1978) states that an appropriate index defines the concept " in a manner consistent with the meaning generally given, explicitly or implicitly, to that term in index free discussion ", and simplicity means " simplicity of interpretation not ease of calculation ". We include the third criterion of ' statistical correctness ' because variations between condition indices are usually considered more interesting than the factors and relationships themselves. It is therefore important that the indices be calculated in a correct manner and that a suitable test be available for their comparison.

In order to illustrate our arguments, a data set consisting of the length and weight measurements of 1240 mature female grey gurnard, *Eutrigla gurnardus* L., captured in the Irish Sea during 1983 was used (Connolly, 1986).

III. REVIEW

Eight forms of index have been used (Table II), which measure either the condition of individual fish (K_1–K_4) or of the whole subpopulation being assessed (K_5–K_8). The first category contains ' condition factors ', the earliest of which (K_1), that of Fulton (1911), assumes isometric growth, i.e. growth with unchanged body proportions and specific gravity. An extension of this expression, K_2 (Ricker,

Table I. A selection of indices used in the study of condition. K, condition index; W, observed fish weight; L, observed fish length; $\hat{W}$, calculated fish weight; C.I., confidence interval; s.e., standard error; GMR, geometric mean regression; LSR, least squares regression; MRT, multiple range tests; length–wt (log), regression of $\log_{10}$ weight on $\log_{10}$ length; ' a ', regression intercept; ' b ', regression slope. See text for further details

Source of study	Form of index		Form of length–wt	Statistical tests
Benfey & Sutterlin (1984) Wahbeh & Ajiad (1985)	$K_1 = W/L^3$.	Mean $K \pm 95\%$ C.I. per month	Not used	ANOVA
Chang & Navas (1984)	$K_1 = W/L^3$.	Mean $K \pm$ s.e. per month; length–wt (log) for sex and sites	Not specified	ANCOVA for ' a ' and ' b '; none for K
Nash (1982)	$K_1 = W/L^3$.	Mean $K \pm$ s.d. per month; length–wt (log) per maturity	GMR and LSR	t-test, ' b ' $=3$; none for K
Opuszynski *et al.* (1985) (larval fish)	$K_1 = W/L.^3$	Mean K per age group	Not used	ANOVA and Duncan's MRT
Hyslop (1987)	$K_{1,6} = W/L^3$ and ' a '.	Mean K per age group	Not used	None used
Linfield (1979)	$K_2 = W/L^b$.	Mean K per month, using ' b ' for each month	LSR	None used
Hails (1983)	$K_3 = W/\hat{W}$.	Mean $K \pm 95\%$ C.I. per month; length–wt (log) for sex	GMR	None used
Mann (1976)	$K_3 = W/\hat{W}$.	Mean $K \pm 95\%$ C.I. per month; length–wt (log)for time, sex and maturity	LSR	None used
Wilson & Pitcher (1983)	$K_3 = W/\hat{W}$.	Mean $K \pm 95\%$ C.I. per month; length wt (log) for sex, maturity and time	Not specified	ANCOVA and Bartlett's test; none for K
Vesey & Langford	$K_7 =$ ' b '.	Length–wt (log) per month	GMR	None used
Weatherley & Gill (1983)	$K_7 =$ ' b '.	Length–wt (log) per experimental group	LSR	Fisher's LSD
Treasurer (1976)	$K_{5,6} =$ ' a ', ' b '.	Length–wt (log) for sex and maturity	Not specified	ANOVA
De Silva (1985)	$K_8 = W_x$.	$K = \hat{W}$ for 20-cm fish per season; length–wt (log) per season	Not specified	Not specified
Basami & Grove (1985)	$K_8 = W_x$.	$K = \hat{W}$ for 30-cm fish per month; length–wt (log) per month	GMR	ANOVA
Wooton & Mills (1979) Goldspink (1979)	$K_8 = W_x$.	$K = \hat{W}$ for 65-mm fish $\pm 95\%$ C.I. per month; length–wt (log) per month	LSR	ANCOVA

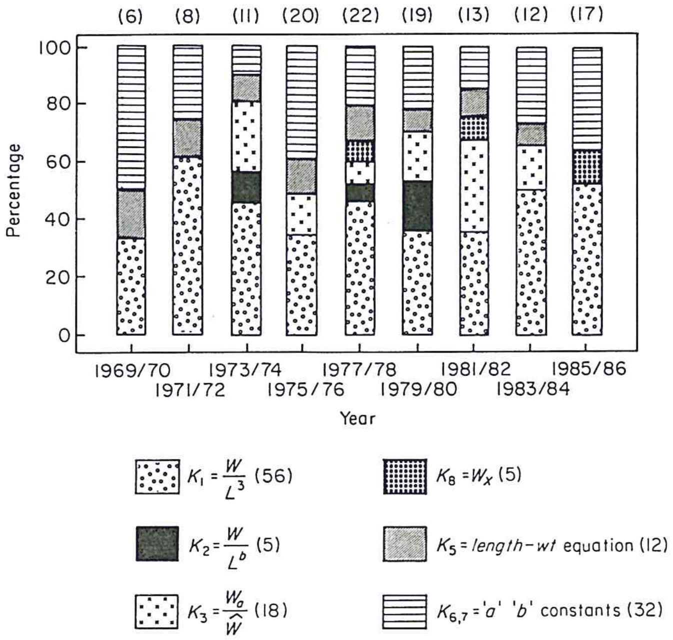

FIG. 1. The six categories of condition indices (K) employed in publications in the *Journal of Fish Biology* and *Transactions of the American Fisheries Society* (1969–1986, inclusive). Numbers in parentheses refer to sample size.

1975*b*), assumes allometric growth, which is valid for most fish species (Le Cren, 1951) but has two major disadvantages: firstly, in order to calculate the regression coefficient, a set of standard conditions must be selected and these are usually difficult to decide upon; secondly, there is some debate about the appropriate model of regression. The problem of this second disadvantage arises with all of the indices which rely on length–weight relationships and is discussed below.

The problem of selecting standard conditions can be overcome by using a ' pooled ' or ' within group ' (not ' total ' as sometimes used) estimate of b, as in K_3 (Le Cren, 1951; Mann, 1973). However, this form of expression must be confined in its uses to comparisons between fish which are homogeneous for b in their length–weight relationships, a prerequisite which seems to have been overlooked by some authors. Homogeneous regression coefficients often occur within stanzas but not usually between them (Bagenal & Tesch, 1978).

The concept of relative condition has been extended by Wege & Anderson (1978), K_4 being an expression of the weight of an individual relative to a standard weight generated from species-specific shape characteristics. Appropriate use of this index requires prior research in order to establish the species-specific parameters (Nielsen & Lampton, 1983).

All of these four measurements (K_1–K_4) relate the actual weight of individual fish to some ' expected weight ' which is calculated as a function of its length. K_1 relates the actual weight to a hypothetical expected weight, or can be considered as the proportion of a cube of side length L which is occupied by a fish of length L. K_2 relates actual weight to a weight which would be expected under ' standard ' conditions, K_3 relates actual weight to a calculated average weight for the population,

TABLE II. Relationships between the forms of condition index based on the equation $E[W|L]=aL^b$, where L is length, W is weight, L^* is a standard length, and b and a are the parameters of the regression of $\log_{10}$ weight on $\log_{10}$ length

Fulton's condition factor	$K_1=aW/E[W|L]$ with $b=3$ i.e. W/L^3
Ricker's condition factor	$K_2=aW/\hat{E}[W|L]$ i.e. W/L^b
Relative condition factor	$K_3=W/\hat{E}[W|L]$ where W is calculated using a 'pooled' estimate of b
Relative weight	$K_4=W/\hat{E}W|$ shape characteristics]
Regression equation of $\log_{10}$ weight on $\log_{10}$ length	$K_5=\hat{E}[W|L]$, i.e. $\log_{10}$ weight $=\log_{10} a+b\log_{10}$ length
a	$K_6=\hat{E}[W|L=0]$
b	$K_7=b$
Weight at standard length	$K_8=\hat{E}[W|L=L^*]$

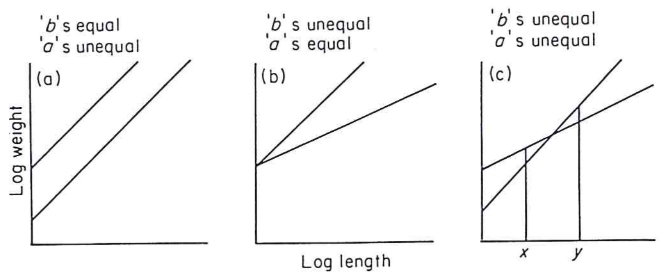

FIG. 2. The effects of variation in the regression parameters on the relative forms of the $\log_{10}$ length–$\log_{10}$ weight relationships. (a) The intercepts on the $\log_{10}$ weight axis (*a*'s) differ but the slopes (*b*'s) are equal, giving parallel lines. (b) The slopes differ but the lines have the same intercept. (c) Both slopes and intercepts differ, resulting in lines which cross.

and K_4 relates it to a weight which is related to the genetically determined shape characteristics of the species.

All of the above four indices fulfil our criteria of simplicity and appropriateness because, firstly, they relate the weight of a fish to its length in a manner which can be readily visualized, and, secondly, they increase as condition, as generally perceived, increases. However, 'condition factors' K_1–K_4 are ratios and the following difficulties are associated with their statistical properties: (i) increased variability in comparison with the variables that were compounded into the ratio; (ii) biased estimation of true mean value of ratio; (iii) unusual, non-normal and possibly intractable distributions of ratios; (iv) tendencies to obscure rather than elucidate the intervariable relationships (Sokal & Rohlf, 1981). Furthermore, in simulation studies, Atchley *et al.* (1976) found large and systematic changes in both the structure and the underlying distributions of data and a pronounced increase in spurious correlation between the ratio variable and the scaling variable. This latter property has been recognized in condition factors, such as K_1, where the value of the factor is correlated with length (Weatherley, 1959). Similar correlations were observed in our test data set for K_1, K_2 and K_3, with K_2 showing the highest level of association ($P<0{\cdot}01$).

In the test data set, within a given month the distributions of K_1, K_2 and K_3 are skewed to the right ($P<0{\cdot}05$) and are very significantly leptokurtic ($P<0{\cdot}001$). In addition, the variances are heterogeneous over the 12 months studied (Scheffé–Box test, $P<0{\cdot}05$). Skewness does not significantly affect either the level of significance or power of *F*-tests, but distributions which are significantly leptokurtic lead to nominal significance levels which are greater that the actual significance levels, and the actual power exceeds the nominal power, especially when there are low numbers of replicates (Glass *et al.*, 1972). The problem of moderately heterogeneous variances is not too serious for overall tests of significance, but single degree of freedom comparisons can be very inaccurate (Sokal & Rohlf, 1981). When sample sizes vary, *F*-tests can be significantly affected by heteroscedasticity, but the actual effect depends on the form of the relationship between the variance and the number of observations used in its calculation. There was no obvious relationship between variance and sample size in the case of the gurnard data. Thus, distribution problems do arise and weaken some of the methods of comparison which have been used with such indices, i.e. mean and confidence limits (e.g., Siddiqui, 1977; Wilson & Pitcher, 1983) and analysis of variance (e.g., Benfrey & Sutterlin, 1984; Wahbeh & Ajiad, 1985). Box–Cox transformations, which are specifically designed to normalize data and to make variances more homogeneous, suggest that the reciprocal of the condition factors might be more appropriate. While this procedure eliminated skewness it did not reduce the kurtosis or heteroscedasticity. In addition, the problems identified by Atchley *et al.* (1976) are particularly pronounced in situations where the denominator in the ratio is highly variable, as it would be in condition factors.

The second major category of index (K_5–K_8, Table II) comprises length–weight relationships and the parameters of linear regressions derived from log transformed data. In the study of fish populations, length–weight relationships serve two different but related functions. They are used both to predict fish weights from known lengths and to measure and analyse condition. These relationships may not filfil our criteria of appropriateness and simplicity. Firstly, when the equation is taken as a whole (K_5), it is not at all easy to imagine the significance of changes in the length–weight functions. Secondly, variation in the regression coefficient (b) and/or the intercept on the ordinate (a) can suggest significant differences among populations and, unless both parameters are considered, valid interpretation of the results is difficult. Many authors have simply used one of the regression parameters, which can be meaningless. When the regression coefficients are homogeneous [Fig. 2(a)] the intercepts act as good indicators of the condition of each group of fish relative to one another. They are, in fact, equal to the $\log_{10} K_2$ for each subgroup, where the b used is a pooled estimate. However, the regression coefficients are commonly heterogeneous, with larger slopes often considered to indicate better condition. This may be true when the intercepts on the ordinate are the same [Fig. 2(b)] but, if they are not equal, those with greater slopes may have lower intercepts [Fig. 2(c)]. Indeed, regression coefficients and intercepts are often inversely related, meaning that predicted weights of smaller fish would be lower when the regression coefficient is large (LeCren, 1951). This problem of the interpretation of length–weight regressions which cross one another also applies, in a less obvious way, to condition factors, and may lead to very misleading results, particularly when fish of different sizes are to be compared; even though their length–weight regressions may be very different, the condition, as represented by condition factors, could be almost identical.

Staples (1975) and De Silva (1985) estimated the weights of fish or arbitrarily fixed lengths from regression equations specific to the groups of fish under consideration and used these as indices of condition (K_8). If regression coefficients are not homogeneous, interpretation of K_8 will be subject to the same difficulties as the regression parameters. If both regression coefficients and intercepts are heterogeneous, changing the chosen standard length may reverse the condition of fish relative to one another, e.g., lengths X and Y in Fig. 2(c).

The statistical problems associated with length–weight relationships are two-fold. Firstly, the form of regression which should be used in the determination of the parameters of the relationship is controversial, and secondly, suitable statistical tests for the comparison of regressions, other than the ordinary least squares predictive regression, are not well known.

The form of regression used depends to a large extent on whether the length–weight relationship is to be used for descriptive or predictive purposes. When total

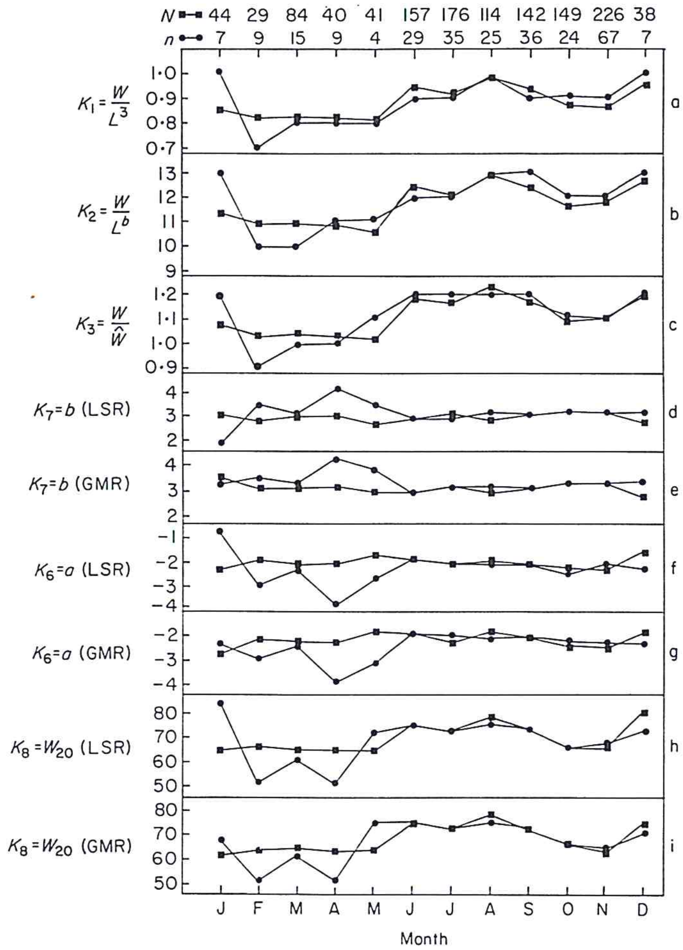

FIG. 3. Seasonal changes in the condition of female grey gurnard, as indicated by nine different indices (a–i). N, the total sample, n, a 20% subsample; LSR, least squares regression; GMR, geometric mean regression.

length–weight relationships or their parameters are being used as indices (K_5, K_6, K_7) the purpose is descriptive. In all other cases it is predictive. Most published work suggests that standard predictive regression should only be applied when the regression is to predict weight from length (e.g., Sokal & Rohlf, 1981; Jensen, 1986). Indeed, Ricker (1973) argues that least squares regression is not correct even for these predictive purposes, because the regression coefficients increase as the lengths used increase. This is similar to the property identified for condition factors, i.e. the values of the factors are correlated with the lengths used in their calculation, because the intercept on the ordinate is equal to $\log_{10} K_2$. Ricker suggests that geometric mean (GM) regression is more appropriate. We examined the condition factor K_2 for the gurnard data and found that the ranked correlation was much less significant when the exponent was derived from GM regression than when it was derived from least squares regression. This suggests that, at least in this situation, Ricker's argument is correct and that GM regression should be used for predictive purposes in the estimation of condition.

Ricker (1973, 1975*a*, 1982, 1984) advocates the use of GM regression for descriptive purposes also, while Jolicoeur (1975) argues that the ordinary major axis is the most accurate form. The GM functional regression seems to be favoured by many biologists (e.g., Rayner, 1985; Jensen, 1986) although statisticians, such as Sprent & Dolby (1980), express a preference for the arguments of Jolicoeur (1975).

The comparison of least squares regression lines and their parameters has been approached through analysis of covariance, or analysis of variance, or *t*-tests. However, the methods of comparing other forms of regression line are not well known and perhaps this is the reason why they are not used more extensively. Dauod *et al.* (1985) used Gabriel's approximate method to compare GM regression coefficients but did not examine the intercepts on the ordinate. Ordinary major axis regressions are usually compared using approximate 95% confidence ellipses (e.g., Wetton, 1987).

IV. CONCLUSIONS

Our test data set has many properties which should minimize the differences between results obtained using the various indices. These include large sample size, similar lengths in each month, and highly significant correlations between length and weight (least squares and geometric mean regressions will be similar). Yet, the seasonal patterns of change in gurnard condition are dictated by the form of index and sample size (Fig. 3). The existence of such differences between the results emphasizes the need for the selection of a suitable index based on an examination of the data set and the assumptions of the index used.

In terms of appropriateness and simplicity, the condition factor, in its various forms, is most satisfactory. In all cases, actual weights are compared with weights that might be expected for hypothetical fish of that length or for fish of that length which act as standards. Thus, one quickly gets an impression of the relative 'well-being' of the fish under investigation. The properties of condition factors as ratios makes valid analysis by parametric statistical techniques difficult, but these difficulties could be circumvented through the use of non-parametric techniques such as Kruskal–Wallis analysis of variance. However, the problem of correlation between condition factors and length means that only populations with similar length distributions should be compared, and Ricker (1975*b*) has advocated the use of K_1 for this purpose.

Relative condition factors (K_3) are inappropriate because of the lack of homogeneity of regression coefficients and forms such as K_2 require the selection of slopes based on standard conditions which are often difficult to select in a meaningful way but, as demonstrated by Bagenal & Tesch (1978), may be the best index when lengths vary significantly among the groups to be compared. The K_1 form assumes that growth is isometric, which is often not the case. However, many fish do have length–weight relationships with regression coefficients not very different from 3. Moreover, the exponent 3 can be considered simply as a method of transforming the linear dimensions of length to the cubic dimensions appropriate in the discussion of weight. The mean gives a resonable impression of the central position of the distributions of such factors but, because of the significant kurtosis, estimates of confidence limits should be considered suspect and not used.

Length–weight relationships (K_5–K_8) are neither appropriate nor simple, because two parameters have to be taken into account when making comparisons. The statistical properties of standard least-squares regressions are well understood but, as pointed out above, GM functional regressions should be used when examining condition. The statistics of the GM regression are not at all well known. We are not aware of any valid tests of the homogeneity of regression coefficients or intercepts on the ordinate. Graphical comparisons are possible but are subject to the usual difficulties of multiple range tests. Thus length–weight functions are similarly not appropriate when considered in the light of our criterion of statistical correctness: research into the statistical properties of such relationships is desirable and should prove rewarding (see also Peters, 1983).

In summary, the present study highlights some of the problems associated with the measurement and analysis of condition. No new indices or statistics are introduced but the assumptions implicit in various techniques are stated explicitly, thus indicating any difficulties involved with their use. Many of the problems identified here may bear out the belief of Smith (1984) that the use of ' carry-over papers ' and easily available computer packages has led to the selection of ' painless means of analysing data without paying attention to the underlying assumptions '. Overall, we believe that the choice of condition index should be based on an understanding of the techniques and should be made after a detailed examination of the properties of the data set.

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