Validation of Mean Lift Estimates for Normal Hovering Flight

J.R. Harvey and J.L. Palmer

Air Vehicles Division
Defence Science and Technology Organisation, Fishermans Bend, VIC 3207 Australia

Abstract

Ellington derived a generalised relationship for the lift created in "normal" hovering flight based on vortex theory. Here, the mass supportable by the wings of biological species capable of hovering has been evaluated by use of Ellington's relation with mean kinematic and morphological data for numerous species obtained from the literature. Reasonable agreement was found between the predictions and the actual masses of 254 insect, 38 hummingbird, and 5 bat species. Several functional entomopter designs were also considered, and it was found that the mass of each was either accurately predicted by Ellington's relation or was over-predicted. Furthermore, the mean lift coefficient necessary for each flyer to hover with "normal" kinematics was evaluated and then compared with published values.

Introduction

Flapping wings provide the highly agile and manoeuvrable means of flight demonstrated by flying organisms, which have inspired the development of numerous flapping-wing micro air vehicles (MAVs). Hovering is an aspect of flapping flight that is desirable for many MAV applications, though it is difficult to replicate mechanically [1-11]. Significant effort has therefore been made to characterise the wing kinematics, aerodynamic forces, and power required to hover [12]; and biological species present an opportunity to measure the relevant quantities and to compare predictions with reality [12-14].

The mean vertical force (lift) generated by a pair of flapping wings is a function of their morphology and kinematics, as well as the airspeed (if any) of the flyer. "Normal" hovering kinematics are characterised by flapping in a horizontal plane and strong wing supination (reversal) during half of the wingbeat cycle, so that the upper surface of the wing faces upward during the "downstroke" and downward during the "upstroke" [15]. This motion is used by most insects and by hummingbirds. Some insects (*e.g.*, dragonflies) flap their wings along an inclined or even vertical plane. These species minimise drag (downward force) during the upstroke by pitching their wings so that they are nearly parallel to the stroke plane. Hovering bats and some small birds use wing deformation and "feathering" into the local flow, rather than complete reversal, during the upstroke, creating most of their net lift on the downstroke [15].

Full equations describing the aerodynamics of hovering flight were derived by Ellington and combined to determine the mass supportable by a typical pair of insect wings [12]. Simple harmonic motion was assumed for the flapping kinematics, and the centroid of the wing area was taken to be at half the wing length. Furthermore, standard values for acceleration due to gravity and air density were absorbed into a constant. With these simplifications, Ellington derived:

$$m = 0.387 \frac{\Phi^2 n^2 R^4 C_L}{AR} , \qquad (1)$$

where m (kg) is the mass that can be supported during hovering, Φ (rad) is the peak-to-peak angular excursion of the wings, n (Hz) is the flapping frequency, R (m) is the wing length, C_L is the mean lift coefficient, and AR is the aspect ratio of the wings ($AR = 2R/\bar{c}$, where $\bar{c}$ is the mean chord length).

The aim of this study is to examine the validity of equation (1) by use of insect, bird, and bat data obtained from the literature. For a given species, the mass supportable by its wings is predicted and then compared with its actual mass. Several functional MAVs are also assessed; and the mean lift coefficient necessary for each flyer to hover with "normal" kinematics is evaluated.

Data Collection

The morphological and kinematic data needed to evaluate equation (1) was gathered from the literature, including data for 254 insect, 38 hummingbird, and 5 bat species. Significant effort was made to use measured data only, unless reasonable estimates could be obtained from data for similar species. Eleven hover-capable entomopters were also evaluated from published reports [1-11].

Greenewalt [13] supplied the most complete set of data for insects, much of which was derived from previous studies; while many other researchers provided additional data for species of the orders Lepidoptera [16], Hemiptera and Homoptera [17], and others. Table 1 presents the insect orders used in the analysis, as well as the common names for many of the species in each order.

Order	Common names
Blattaria	cockroaches
Coleoptera	beetles
Diptera	houseflies, mosquitoes, craneflies
Hemiptera/Homoptera	aphids, cicadas, whiteflies
Hymenoptera	bees, wasps, ants, sawflies
Lepidoptera	butterflies, moths
Mecoptera	scorpionflies
Neuroptera	lacewings
Odonata	dragonflies, damselflies
Orthoptera	grasshoppers, crickets, locusts
Thysanoptera	thrips

Table 1 The insect orders used in the analysis and the common names for some of the species within each order.

For some insects, a measured value of stroke amplitude was not provided, and the mean value for similar species was used instead. For example, for insects of the order Coleoptera, stroke amplitude values of 160–180° were used; and, for Lepidopterans, stroke amplitudes ranged from 75–170°, depending on family. In a very few cases (five Dipteran: Tipulidae), the wing aspect ratio was estimated from those for members of the same family.

Measured lift coefficients for the various insects were generally unavailable, therefore a value of 2 was assumed for the majority of them (and for hummingbirds), based on a recommendation by Ellington [12]. Odonates tend to have higher lift coefficients than

other insects, thus a value of 3 was assumed [15]. To account for the fact that some insects, such as dragonflies and locusts, have tandem wing pairs, the forces predicted to be created by their forewings and hindwings (in isolation) have been summed to estimate the total mass supportable by their wings.

Data for hummingbirds in hovering flight was obtained from several sources [14, 18, 19]. For about half the species, values for wing aspect ratio were not available. Estimates were made by use of a dimensional relationship between wingspan and wing area derived by Greenewalt [19] through a regression analysis of the available data, which are strongly correlated for hummingbirds.

A survey of the literature on hovering bats revealed only a few flapping-frequency measurements [20-24]. In a single case [20], the stroke amplitude was not supplied and thus has been assumed to be 120°, based on the values for other bats; and the lift coefficient has been assumed to be 3.5 [15]. Bats are known to generate relatively little lift on their wings' upstroke; thus, equation (1) has been applied with values of stroke amplitude equal to one-half of the values reported in the literature, to attempt to account for the difference between their hovering kinematics and "normal" kinematics.

Data was also obtained for various functional entomopters, including the Microbat [1], the Butterfly Type Ornithopter (BTO) [2], various versions of DelFly [3-5], the Harvard RoboFly [6], the SF-3 Mentor [7], and other entomopters developed by groups in Japan (the Kawamura clapper) [8], the Netherlands (the Resonant-ring clapper) [9], India (the Bangalore MAV) [10], and Korea (beetle) [11]. To ensure the credibility of the collected data, only entomopters that have demonstrated free flight were included in the analysis.

As with many of the biological flyers, a value of 2 was assumed for the lift coefficient for each entomopter; and MAVs with two pairs of wings (*e.g.*, Mentor and the DeFlys) were treated similarly to dragonflies and other four-winged flyers: the contribution of each wing pair was computed separately and summed to obtain the total lift. This approximation is justified by a desire here to validate equation (1) by use of only the gross parameters describing each flyer.

Flapping Frequency and Wing Length

The data used in this study may be examined in its "raw" form by investigating the relationship between flapping frequency and wing length, as shown in Figure 1. Greenewalt [19] established that, under certain conditions, these quantities follow the principle of a damped, driven oscillatory system. If species were dimensionally similar, the relationship between their flapping frequency and wing length would be that of a classical oscillator: $nR = \alpha$, where α is a constant. Given that the lack of dimensional similarity, he proposed a more appropriate form: $nR^\beta = \alpha$, where β is another constant. From an analysis of insect and hummingbird data, he demonstrated that the data was well fit by the equation of a classical oscillator (*i.e.*, $\beta \approx 1$) and that the departure was barely significant.

The present analysis yields similar results (Figure 1), where the constant, $nR = \alpha = 2$, was chosen here to illustrate the form for a classical oscillator. The data for hummingbirds follows the slope of the line closely, as does that for the majority of the Hymenopterans and Lepidopterans of the family Sphingidae (hawk moths, sphinx moths, and hornworms). The other insect families and bats broadly follow the theoretical trend; however, reliable equations cannot be deduced from the scattered datasets.

The data for entomopters in Figure 1 is similarly seen to loosely follow the trend, but not to be described adequately by the equation for a classical oscillator. Unlike insects within a particular order, the MAVs have a variety of designs with great variation in wing aspect ratio and general layout (*e.g.*, two wings *vs.* four); thus, they strongly violate the assumption of geometric similarity required for treatment as a classical oscillator.

Lift Estimates for Hoverers

The morphological and kinematic data for each natural or mechanical flyer was input to Ellington's equation to predict the mass supportable by its wings. This value (m_{pred}) is displayed as a function of the actual mass of the flyer in Figure 2a. The scatter in the data for insects is relatively large (particularly for Dipterans) and may be the result of errors in the data; however, a line representing equivalence between the predicted and actual masses is seen to adequately describe most of the biological data.
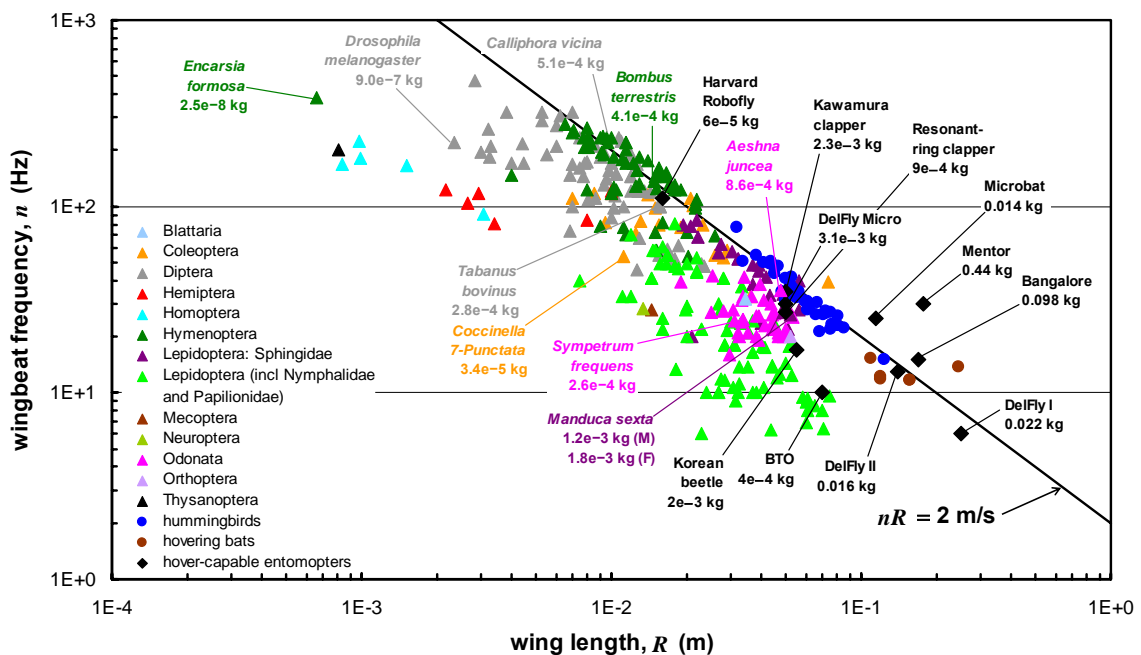

Figure 1. Wingbeat frequency *vs.* wing length for natural and mechanical hoverers. The solid line is of the form expected for a classical oscillator. The data points for several of the insect species and each entomopter are labelled by name and its mass is provided.
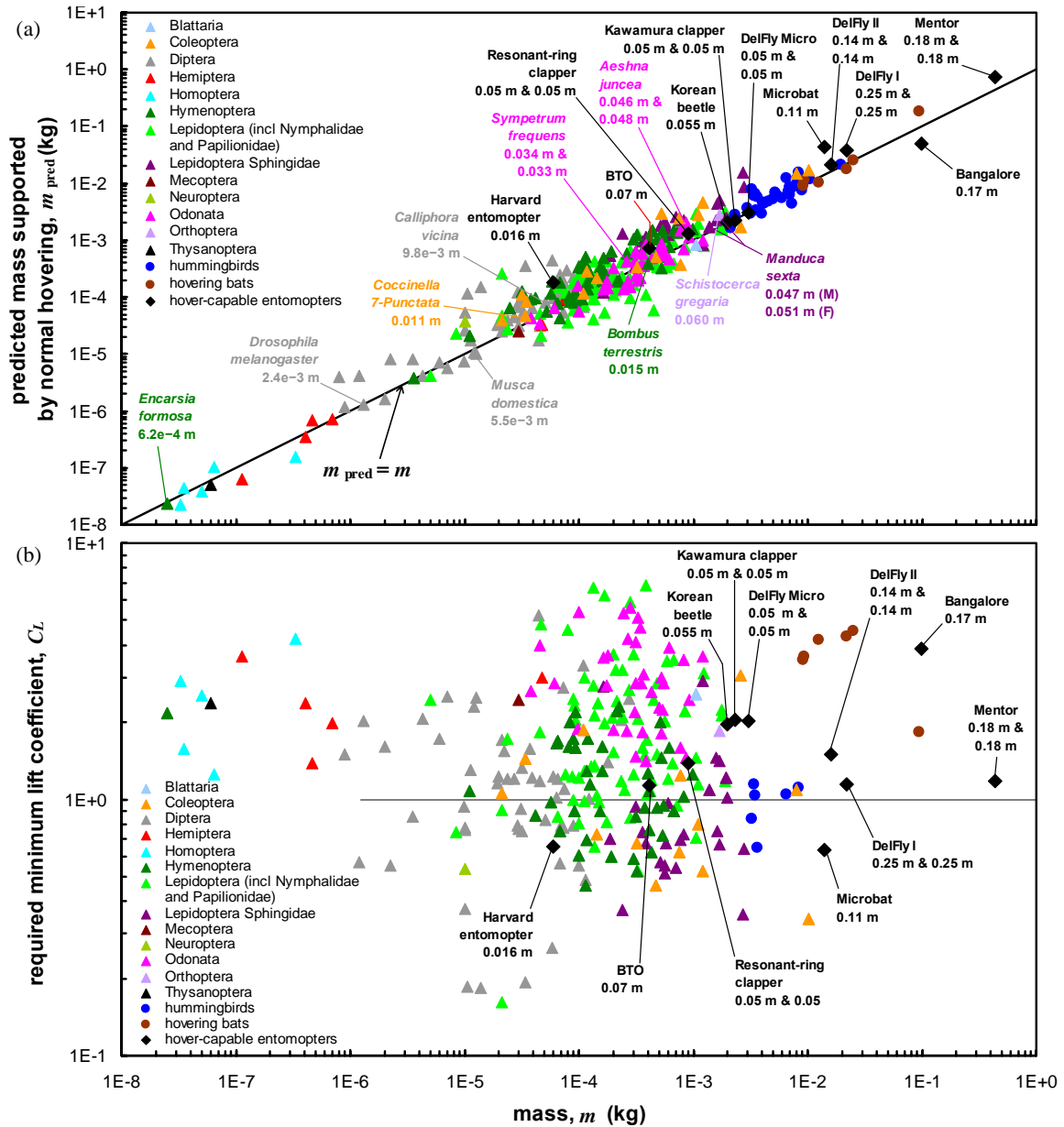
Figure 2. (a) The mass predicted to be supportable by the wings of a variety of hover-capable flyers, plotted as a function of their actual masses. Data points are labelled with the names of the insect species or MAV and the wing lengths of each flyer are provided. (b) The minimum lift coefficient required to support the mass of a given flyer, estimated using equation (1) and the known physical characteristics of each flyer.

A linear regression analysis was performed to quantify the strength of agreement between the predicted and actual masses of the biological flyers. To ensure that the regression was not biased toward the larger species, the common logarithms of both values were fitted. The slope of the 'line of best fit' was ~1 (0.9937), and a correlation coefficient of 0.94 (indicative of a very strong correlation) was obtained, thus supporting the broad validity of equation (1) for the entire class of natural hoverers.

The mass supportable by the wings of each entomopter was also predicted with equation (1). The results are compared with those for the biological flyers in Figure 2a. With the exception of the Bangalore MAV, the mass of each MAV is well predicted by Ellington's relation or is over-predicted (by up to a factor of 6).

Conversely, equation (1) may be used to infer the lift coefficient necessary for a given set of wings to support a given mass in hovering flight. The minimum lift coefficient of each flyer was evaluated from its mass, geometry, and kinematic characteristics. As shown in Figure 2b, the results for insects range from an unrealistic low of ~0.2 (for species for which the predicted mass

supportable was much greater than the actual mass) to a high of nearly 7 (when the reverse was true); however, the minimum lift coefficients of 90% of the insects are between 0.52 and 4.5, with a mean of 1.8. Odonates, as anticipated, were found to require significantly higher lift coefficients than other insects. On average, a minimum lift coefficient of 3.0 was found for Odonates; whereas for all other insects the mean minimum lift coefficient was found to be 1.6. Markedly lower values (with means of ~1) were obtained for Sphingidae and Coleopterans.

Lift coefficients were evaluated for six hummingbird species for which all necessary parameters were available directly from the literature (*i.e.*, no estimations for stroke amplitude were made). The minimum lift coefficient required for hummingbirds was found to have a mean value of ~1, which is significantly lower than the value of 1.8 obtained by Weis-Fogh [14] through a quasi-steady analysis; whereas, for bats, the lift coefficient required for hovering was found to be, on average, 3.7, which is similar to the value of 3.5 given by Ellington [15]. Owing to the scatter in the data, only mean differences amongst the insect orders and the other classes of flyers are identifiable.

With the exception of the Bangalore MAV, Figure 2b shows that hovering entomopters require minimum lift coefficients comparable to those of most insects and hummingbirds. On average, a lift coefficient of 1.4 is required, and the root-mean-squared deviation of the data is ± 35% of this value. In contrast, the data for the Bangalore MAV, which has a single wing pair, indicates that its minimum required lift coefficient is significantly higher than those of the other entomopters and of most insects (particularly insects with single functional wing pairs, *e.g.*, Lepidopterans or Coleopterans).

It may be anticipated that mechanical hoverers would have inherently lower lift coefficients than comparable natural flyers and that they would thus be required to use higher flapping rates or stroke amplitudes for a given wing geometry (size and aspect ratio), but that appears not to be the case for the entomopters examined here. Indeed, one of the entomopters appears to exceed the performance expected from comparisons with similar natural flyers; although this single instance is unexplained.

Conclusion

Many of the details of wing geometry and kinematics have been neglected here in favour of the use of gross parameters describing the size, aspect ratio, flapping rate, and stroke amplitude of the wings of hovering flyers. Furthermore, Ellington's equation, derived for normal hovering flight with a single wing pair, has been adapted for use with tandem and clapping wing pairs and for cases with lift only during the downstroke of the wings. Nonetheless, the relationship has been shown to adequately represent the data for a wide variety of natural and mechanical hoverers, including numerous insects, hummingbirds, and bats and the hovering entomopters for which adequate data is available.

This has practical implications for entomopter design, because Ellington's equation may be used to scale lift estimates with the gross characteristics of an entomopter intended for hovering flight. The validated equation thus provides a useful guide to, for example, the flapping frequency or stroke amplitude necessary to support a given mass with a given set of wings.

References

[1] Pornsin-sirirak, T.N.*, et al.*, Microbat: A Palm-Sized Electrically Powered Ornithopter, in *NASA/JPL Workshop on Biomorphic Robotics*, 2001.

[2] Tanaka, H.*, et al.*, Flight Dynamics of a Butterfly-Type Ornithopter, in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2005, pp. 310–315.

[3] Technical Data DelFly Micro, Delft University of Technology, the Netherlands, July 2008. Available from: http://www.tudelft.nl/live/pagina.jsp?id=0e64952b-77fe-4df4-98d6-6ed62a750539&lang=en.

[4] Bradshaw, N.L. & Lentink, D., Aerodynamic and Structural Dynamic Identification of a Flapping Wing Micro Air Vehicle, in *26th AIAA Applied Aerodynamics Conference*, 2008.

[5] de Croon, G.C.H.E.*, et al.*, Design, Aerodynamics, and Vision-Based Control of the DelFly, *International Journal on Micro Air Vehicles*, **1**(2), 2009, pp. 71–97.

[6] Wood, R.J., Liftoff of a 60mg Flapping-Wing MAV, in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2007, pp. 1889–1894.

[7] Zdunich, P.*, et al.*, Development and Testing of the Mentor Flapping-Wing Micro Air Vehicle, *Journal of Aircraft*, **44**(5), 2007, pp. 1701–1711.

[8] Kawamura, Y.*, et al.*, Clapping-Wing Micro Air Vehicle of Insect Size, in *Biomechanisms of Swimming and Flying*, eds. Kato, N. & Kamimura, S., 2008, Toyko, Springer.

[9] Bolsman, C.T., Goosen, J.F.L. & van Keulen, F., Design Overview of a Resonant Wing Actuation Mechanism for Application in Flapping Wing MAVs, in *European Micro Aerial Vehicle (EMAV) Conference*, 2009.

[10] Fenelon, M.A.A., Biomimetic Flapping Wing Aerial Vehicle, in *Proceedings of the International Conference on Robotics and Biomimetics*, 2009.

[11] Nguyen, Q.V.*, et al.*, Characteristics of a Beetle's Free Flight and a Flapping-Wing System That Mimics Beetle Flight, *Journal of Bionic Engineering*, **7**, 2010, pp. 77–86.

[12] Ellington, C.P., The Novel Aerodynamics of Insect Flight: Applications to Micro-Air Vehicles, *Journal of Experimental Biology*, **202**(23), 1999, pp. 3439–3448.

[13] Greenewalt, C.H., Dimensional Relationships for Flying Animals, *Smithsonian Miscellaneous Collections*, **144**(2), 1962, pp. 1–46.

[14] Weis-Fogh, T., Energetics of Hovering Flight in Hummingbirds and in Drosophila, *Journal of Experimental Biology*, **56**(1), 1972, pp. 79–104.

[15] Ellington, C.P., The Aerodynamics of Hovering Insect Flight. I. The Quasi-Steady Analysis, *Philosophical Transactions of the Royal Society of London B*, **305**(1122), 1984, pp. 1–15.

[16] Bartholomew, G.A. & Casey, T.M., Oxygen Consumption of Moths During Rest, Pre-Flight Warm-up, and Flight in Relation to Body Size and Wing Morphology, *Journal of Experimental Biology*, **76**(1), 1978, pp. 11–25.

[17] Byrne, D.N., Buchmann, S.L. & Spangler, H.G., Relationship between Wing Loading, Wingbeat Frequency and Body Mass in Homopterous Insects, *Journal of Experimental Biology*, **135**(1), 1988, pp. 9–23.

[18] Epting, R.J., Power Output and Wing Disc Loading in Hovering Hummingbirds, *The American Naturalist*, **107**(958), 1973, pp. 761–765.

[19] Greenewalt, C.H., The Flight of Birds, *Transactions of the American Philosophical Society*, **65**(Part 4), 1975, pp. 1–67.

[20] Norberg, U.M. & Rayner, J.M.V., Ecological Morphology and Flight in Bats (Mammalia; *Chiroptera*): Wing Adaptations, Flight Performance, Foraging Strategy and Echolocation, *Philosophical Transactions of the Royal Society of London B*, 1987, pp. 101–118.

[21] Aldridge, H.D.J.N., Vertical Flight in the Greater Horseshoe Bat *Rhinolophus Ferrumequinum*, *Journal of Experimental Biology*, **157**(1), 1991, pp. 183–204.

[22] Norberg, U.M.*, et al.*, The Cost of Hovering and Forward Flight in a Nectar-Feeding Bat, *Glossophaga Soricina*, Estimated from Aerodynamic Theory, *Journal of Experimental Biology*, **182**(1), 1993, pp. 207–227.

[23] Dudley, R.E. & Winter, Y., Hovering Flight Mechanics of Neotropical Flower Bats (Phyllostomidae: Glossophaginae) in Normodense and Hypodense Gas Mixtures, *Journal of Experimental Biology*, **205**(23), 2002, pp. 3669–3677.

[24] Hedenström, A.*, et al.*, High-Speed Stereo DPIV Measurement of Wakes of Two Bat Species Flying Freely in a Wind Tunnel, *Experiments in Fluids*, **47**(5), 2009, pp. 923–932.